THE EFFECT OF REGULATION BY TWO IMPOUNDMENTS ON AN ACID, BLACKWATER, CAPE MOUNTAIN STREAM.

by

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requirements for the Degree of Doctor of Philosophy
in the Zoology Department
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for my parents,

Michael and Sylvia Byren

and

for my husband,

Dave

for their continuous love and support

DECLARATION

This thesis reports the results of original research which I have carried out in the Department of Zoology, University of Cape Town, between 1986 and 1992. None of it has been submitted in whole or in part for any other degree and any technical assistance I have received is fully acknowledged.

Signed by candidate

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B A Gale

CONTENTS

ABSTRACT

The world-wide proliferation of dams in the last few decades has necessitated a fuller understanding of the effects of stream regulation but has also provided a setting for testing and developing basic theories of stream ecology. Two important concepts in stream ecology, the River Continuum Concept (RCC) and the Serial Discontinuity Concept (SDC), required investigation as to their applicability to entire river systems in the Southern Hemisphere. The RCC hypothesises that biological communities are structured in a predictable fashion from the source to the mouth of a river in relation to physical environmental gradients along the stream continuum. The SDC proposes that a major impoundment at any position on a river system will cause a longitudinal shift in a given parameter (physical or biological) which will cause a discontinuity in the stream continuum. A certain distance is then required for the stream to return to its normal position in the continuum, and this is termed a 'discontinuity distance'.

The effect of regulation by multiple impoundment on the 'discontinuity' (recovery) 'distances' for various physical, chemical and biological attributes of the Palmiet River (a short, steep gradient, cool, acid, low nutrient system) was investigated in a two year study. Two zones of the river were identified for study: one below an upper-reach impoundment, Nuweberg, and one below a middle-reach impoundment, Arieskraal, as they provided sufficiently long stretches of unperturbed river (7 km and 37 km) over which recovery distances could be investigated. Sampling was undertaken monthly for 27 months from February 1986 to April 1988. Eleven sites were chosen along the length of the river: one in the pristine upper reaches, one site above and 3 sites below Nuweberg, a site on the river as it passes through the villiage of Grabouw, one site above and three sites below Arieskraal and a site on a tributary, the Klein Palmiet, from which water is abstracted into Arieskraal. The values of the variables downstream of the impoundment are said to increase or decrease with respect to the "above-impoundment" value.

Median temperatures, pH and alkalinity increased below Nuweberg, but decreased below Arieskraal, whereas the converse was true for soluble reactive phosphate. Seasonal flow regime reversal occurred below Nuweberg and seasonal flow constancy below Arieskraal; there were seasonal shifts in temperature and a dampening of the annual temperature range below both impoundments; and seasonal shifts in alkalinity below Arieskraal. At least partial recovery was noted in all cases, but in some instances, recovery was incomplete to the estuary.

Quantities of total suspended solids comprising predominantly ultra-fine particulate matter increased from source to mouth with uncharacteristic increases below both impoundments. The larger size fractions (coarse, fine and very fine) showed highly variable downstream changes and varying responses to regulation, as did the CPOM:FPOM ratio. There was a noticeable increase in particulate loads during autumn/winter yet the highest percentage organics was recorded in summer/autumn. There was a strong positive correlation

($p < 0.005$) between annual discharge and annual suspended particulate loads. Recovery distances were variable and the RCC and SDC were found to apply in only some sections of the river.

A total of 36 macroinvertebrate taxa was recorded in the drift of which seven taxa, 4 benthic and 3 zooplanktonic, predominated. Below both impoundments median drift density and median drift biomass increased, both variables decreasing to below source levels within 3 km of the impoundments. Drift taxonomic richness decreased below both impoundments and did not recover fully before entering the next impoundment (below Nuweberg) or before reaching the estuary (below Arieskraal). The effect of impoundments on neither plankton concentration nor (drift) taxonomic richness corresponded well with the predictions of the SDC.

A total of 79 macroinvertebrate taxa was recorded in the benthic samples. Of the 58 taxa analysed, 40 either increased or decreased in median number below one or both of the impoundments. Species diversity decreased noticeably below Nuweberg and varied greatly below Arieskraal. Benthic macroinvertebrate species richness decreased markedly below both impoundments. Below Nuweberg the chironomid larval component of the population increased, whereas below Arieskraal the simuliid component of the community increased but within 3 km the chironomids again became dominant. Trichopteran numbers increased markedly below Nuweberg and decreased below Arieskraal.

In order to clarify the more direct effects of stream-lake-stream interactions, the two impoundments, as well as their respective inflows and outflows, were sampled in January and June 1988. The downstream sites corresponded well with the physico-chemistry of the bottom sites at the discharging ends of each impoundment. Below Nuweberg zooplankton species densities in the outflow corresponded well with the bottom water at the discharging end of the impoundment, whereas below Arieskraal most species showed higher densities in the outflow than in the bottom water at the discharging end.

Since the Palmiet River has an entire length of only 74 km, even recovery distances of 3 km represent a severe perturbation to the system. The use of a short, 4th order stream was a deliberate choice as in South Africa the longest river, the Orange River, only reaches 7th order, and most systems only reach 4th or 5th order. Accordingly the Palmiet is more representative of the bulk of South African rivers and the applicability of the RCC and SDC could be tested at this level. The use of theories and models to predict ecosystem response to perturbation, in order to manage river ecosystems, must be approached with great caution. The community composition of the benthic macroinvertebrates in the Palmiet River and their response to impoundment has highlighted some difficulties in predicting the biological impacts of impoundment. There are many factors which need to be taken into account if modelling of the downstream effects of impoundment on riverine biotas is to be attempted.

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INTRODUCTION

Most of the primary civilisations of the world emerged in, or near, river valleys. The construction of dams and other hydraulic structures is, therefore, one of the oldest branches of engineering (Baxter, 1977). The earliest dams were probably built for irrigation, flood control, and water supply. Later, water was impounded so that its subsequent controlled release could provide a source of energy, first using waterwheels and later hydro-electric generators. Usually the role of water storage reservoirs is to impound water during periods of high flow so that the water may be utilised during periods of low flow (Baxter, 1977). Man is of course not the only dam-building animal. The dams of beavers, although smaller than many of those made by man, can cause spectacular changes in certain areas (Baxter, 1977; Naiman *et al.*, 1988). The utilisation of rivers around the world has increased greatly in recent years, as global water resources become stressed by human population growth. Accordingly, research into river systems has also increased, as can be seen in reviews such as those by Ward (1976a), Gore (1977), Davies (1979) and Petts (1984), and in syntheses edited by Ward and Stanford (1979a), Lillehammer and Saltveit (1984), Davies and Walker (1986) and Craig and Kemper (1987), particularly in regard to how river ecosystems function and how they respond to disturbance.

The demand for water in South Africa

South Africa (22°S to 35°S and 15°E to 32°E: Figure 1a,b) has a low conversion of mean annual precipitation (MAP) to mean annual run-off (MAR). Only 8.6% of the MAP for the sub-continent (497mm per annum) is converted to run-off, one of the lowest conversions of rainfall to run-off of any area of the world (Figure 2) (Alexander, 1985).

The remainder of the MAP is "lost" through evaporation and to groundwater. The distribution of water across the sub-continent is also spatially uneven. Rivers on the eastern escarpment yield two-thirds of the run-off (Figure 1b), while one-third of the land mass yields a mere 1% of the total runoff (B R Davies pers. comm.).

South African stream ecosystems are facing increasing stresses caused by excessive utilisation of water in a greatly water-stressed region (Figure 3 and Alexander, 1985). Owing to the geomorphology of the land mass, rivers supply almost all of the water for a

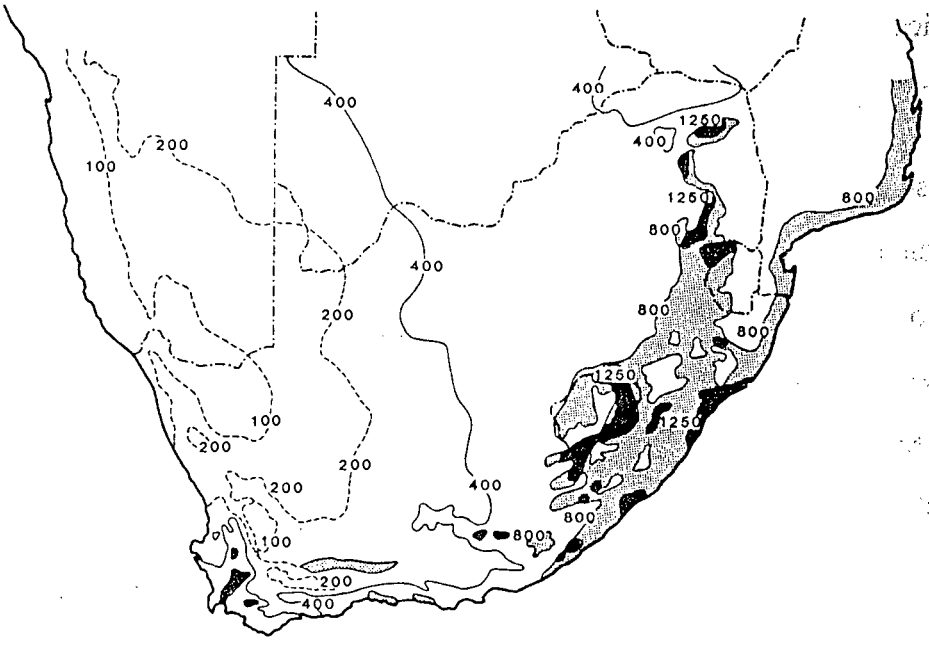

Figure 1a: Rainfall isohyets (mm per annum) for southern Africa. Note the dramatic decline in rainfall to the west (from Davies and Day, 1986).

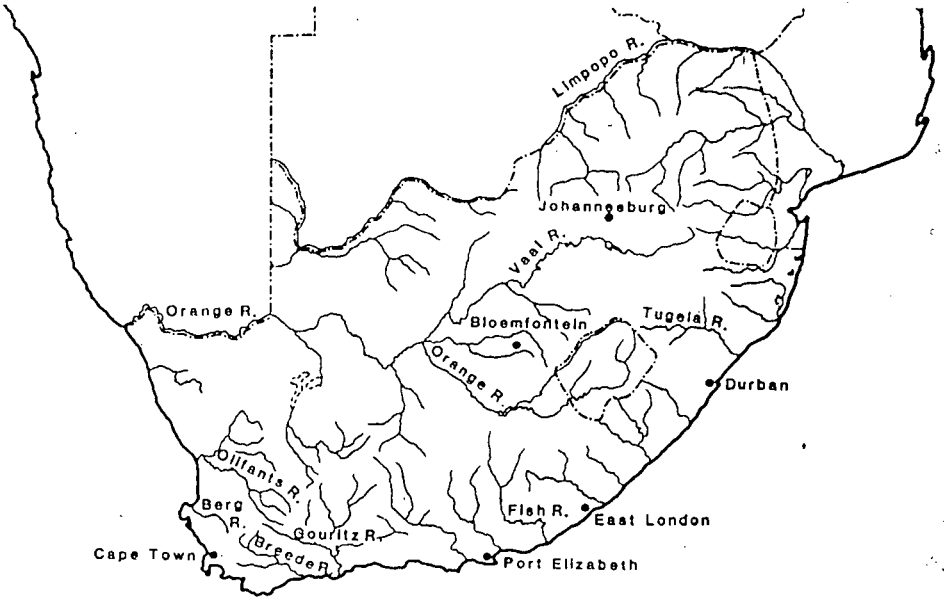

Figure 1b: The major river systems of South Africa: most flow west-east or north-south and are relatively short. The longest system is the Orange-Vaal which flows westwards through increasingly dry country (from Davies and Day, 1986).

rapidly expanding population. Few, if any, large or medium sized rivers in South Africa are not disrupted by impoundment (Allanson *et al.*, 1990). There are 519 impoundments in South Africa with a capacity greater than 50 000 m^3 and these capture 50% of the MAR of the country (Department of Water Affairs, 1986; Allanson *et al.*, 1990).

Multiple storage structures have been constructed for hydroelectric power production, potable domestic consumption, industrial uses, and agriculture, and the idea of 'recovery' from discontinuities caused by dams has assumed importance amongst the scientific and management communities in that it may provide understanding for the rational management of regulated lotic systems. Research into ecological functioning using such approaches may well assist in the design of future dams and alter the release patterns of present and future dams.

Water requirements for the south-western Cape, South Africa

The south-western Cape of South Africa, although occurring in a mediterranean climatic region with a fairly high and strongly seasonal winter rainfall, is situated in the generally drier region in the west of the country (Figure 1a). The city of Cape Town, one of the largest cities in South Africa, is supplied with water from the mountain streams of the south-western Cape. The Hottentots Holland Mountain Range (see Study Area, Figure 3, p 27) unfortunately supplies more water to its eastern side, whereas the greatest population occurs on the western side of the mountains. Thus water is pumped across catchment boundaries into the Greater Cape Town Metropolitan Area (GCTMA).

The South African Department of Water Affairs and Forestry (DWAF) has stated that "the rising demand for water in the GCTMA requires that all available resources should be considered for development: surface and subsurface water sources and unconventional water sources" (DWAF, 1991). The Palmiet River, a 74 km long acid, blackwater, mountain stream, lying just to the east of the Hottentots Holland Mountain range, is one of the surface water resources identified by the DWAF for possible development. In the 1970s the then South African Department of Water Affairs (now DWAF) put forward proposals for increased utilisation of the Palmiet River. These proposals included the construction of a fifth impoundment on the river, Kogelberg, between the then two lowermost impoundments on the system, Applethwaite and Arieskraal (see Study Area, Figure 3, p 27). The new

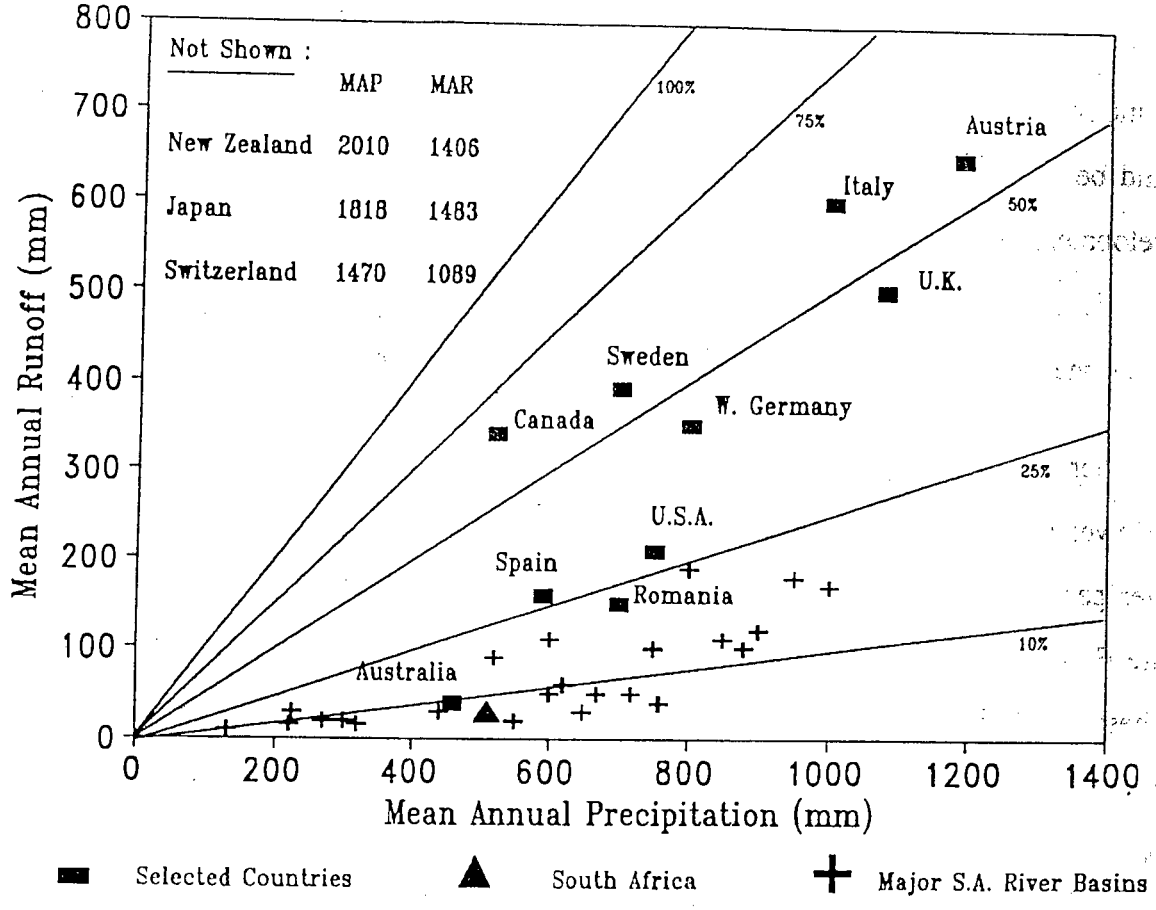

Figure 2: Relationship between Mean Annual Runoff and Mean Annual Precipitation (from Alexander, 1985).

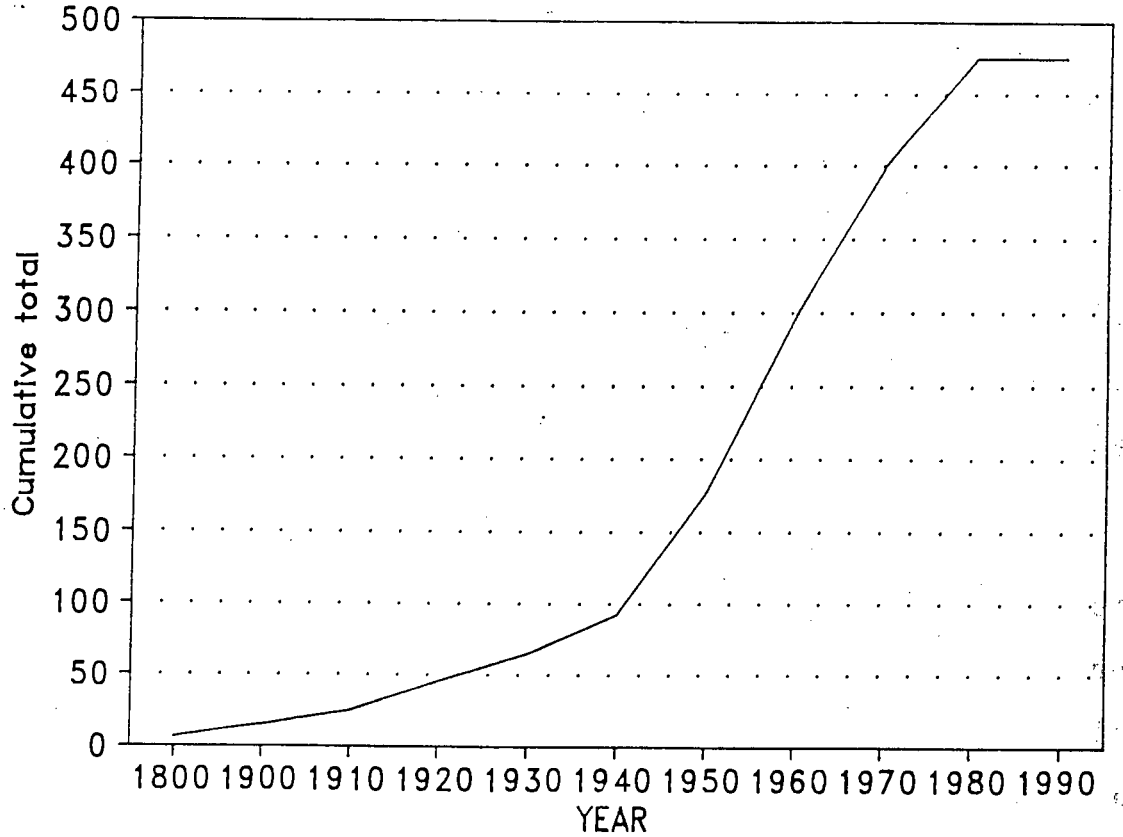

Figure 3: The cumulative increase in the number of dams in South Africa over the past two centuries (B R Davies, pers. comm.)

impoundment would, together with an offstream storage facility, be used as a pump-storage scheme for the generation of electricity. The top reservoir, Rockview, a rock-fill reservoir, would be situated 2 km away in the Hottentots Holland Mountain Range. This phase of development was completed in 1988 and incorporates a facility, planned to come on-stream in 1993, for transferring water from the Palmiet River, *via* Rockview, to Steenbras, at present the main water supply reservoir for Cape Town.

A further phase of development of the Palmiet River would be to harness the run-off from the lower reaches which is, at present, "lost" to the sea. The lower reaches of the Palmiet River pass through a pristine mountain region of dense natural vegetation, the Kogelberg State Forest (KSF). The KSF has a dense population of indigenous flora with one of the highest percentages of endemic species per unit area in the world. The KSF is thus of prime conservation and specifically botanical importance and is presently being considered by UNESCO as the core area of a biosphere reserve. Several proposals to dam the lower reaches of the Palmiet River have been put forward by DWAF, and there is at present much debate as to the best means of utilising the water which would be of benefit to all parties concerned: the man-in-the-street, conservationists, ecologists and land-users (i.e. domestic water users, industry, farmers and nature-lovers).

Theoretical approaches to river ecosystem functioning

Several recent concepts concerning river ecosystem functioning have, been formulated in North America during the last two decades. These include the River Continuum Concept (RCC, Vannote *et al.*, 1980), the Serial Discontinuity Concept (SDC, Ward and Stanford, 1983a) and the Intermediate Disturbance Hypothesis (IDH, Ward and Stanford, 1983b). The basic tenets of these concepts are briefly described below.

River Continuum Concept: The RCC hypothesises that "the structural and functional characteristics of stream communities are adapted to conform to the most probable position or mean state of the physical system" (Vannote *et al.*, 1980). Thus biological communities are said to be structured in a predictable fashion from the source to the mouth of a river in relation to physical environmental gradients along the stream continuum. Thus, the RCC hypothesises that producer and consumer communities characteristic of a given reach become established in harmony with the dynamic physical conditions of the channel.

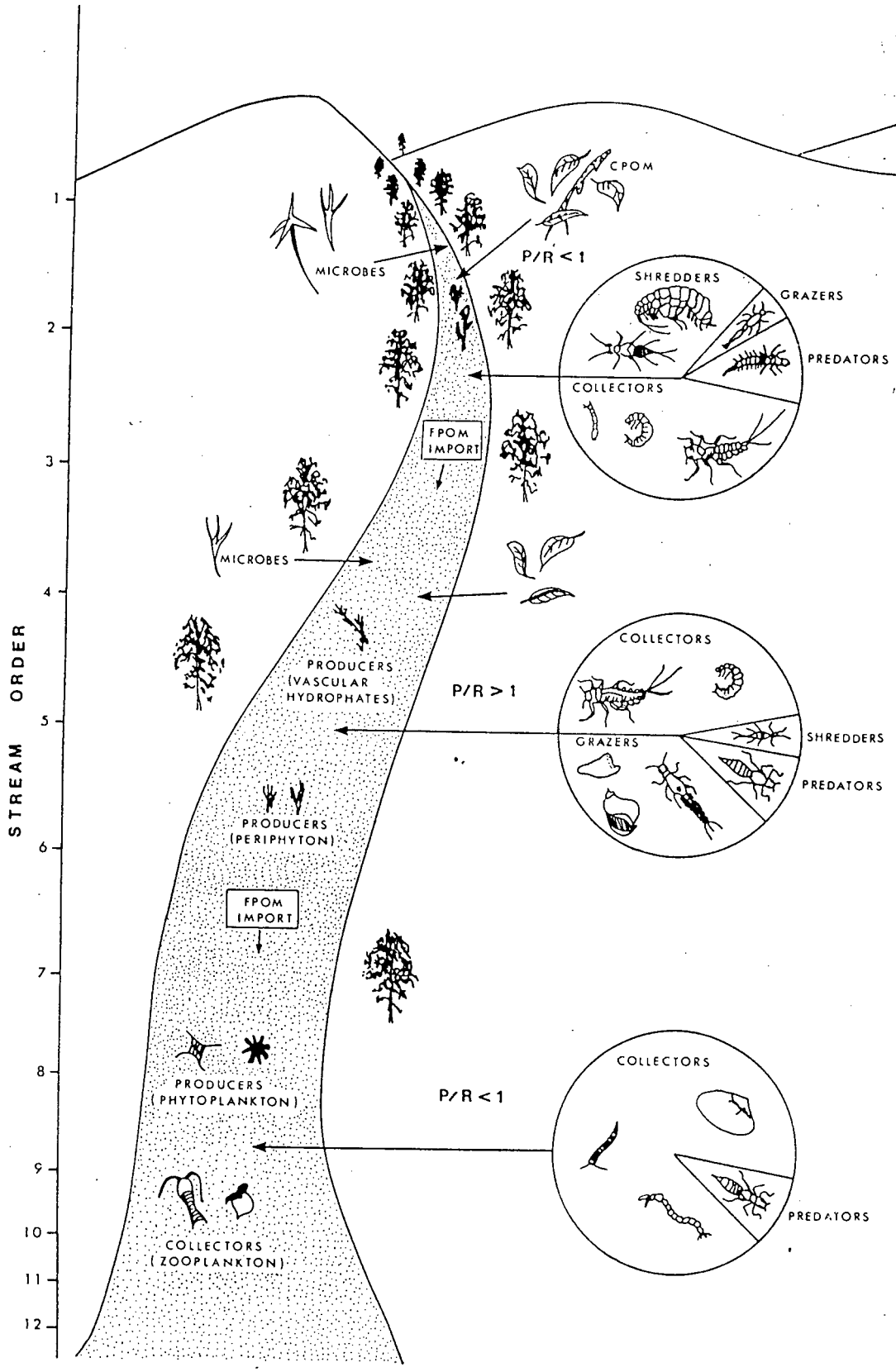

Figure 4: A simplified representation of the RCC (from Davies and Day, 1986; modified from Vannote *et al.*, 1980)

Imported organic material, the chief energy source of most headwater streams, is processed by successive downstream communities that render it into finer particles (Figure 4 and Walker, 1985). Vannote *et al.* (1980) theorise that "biological communities developed in natural streams possess energy processing adaptations which involve minimum energy loss". Downstream communities are fashioned to capitalise on the inefficiencies of upstream processes (Armitage 1984).

Many studies (e.g. Armitage, 1977; Brooker and Hemsworth, 1978) undertaken prior to the publication of the RCC support the ideas put forward by Vannote *et al.* (1980). Subsequently, much work has been done to test different aspects of the RCC, such as downstream changes in biota (e.g. Bruns *et al.*, 1984; Bruns and Minshall, 1985; Culp and Davies, 1982), and alterations in P/R ratios (Bott *et al.*, 1985) along the length of river systems. Unfortunately, the concept was based on research done on the long, temperate streams of North America which have their headwaters in forested mountain areas. The concept may be difficult to apply to short streams with open canopied headwaters. The idea that the stream is a dynamic ecosystem that changes in a continuous fashion with respect to longitudinal environmental and resource gradients is, however, a useful framework on which to base stream ecosystem studies.

Serial Discontinuity Concept: The SDC (Ward and Stanford, 1983a) was developed as the result of other theoretical concepts of lotic ecosystems which viewed stream systems as uninterrupted continua (e.g the RCC). Ward and Stanford (1983a) noted that few riverine ecosystems remain free-flowing over their entire course; in fact, regulation by dams has resulted in an alternating series of lentic and lotic reaches. The SDC proposes that a major impoundment at any position on a river system will directly and indirectly affect all ecological aspects of the downstream lotic ecosystem at some level of resolution. A longitudinal shift in a given parameter (physical or biological) as a result of river regulation (Figure 5 and Ward, 1984) will cause a discontinuity in the stream continuum. A certain distance is then required for the stream to return to its normal position in the continuum, and this is termed a 'discontinuity distance' (Ward and Stanford, 1983a). Ideally, pre-impoundment data should be known before measurements of 'discontinuity' can be attempted but since no pre-impoundment data were available for this system I have preferred

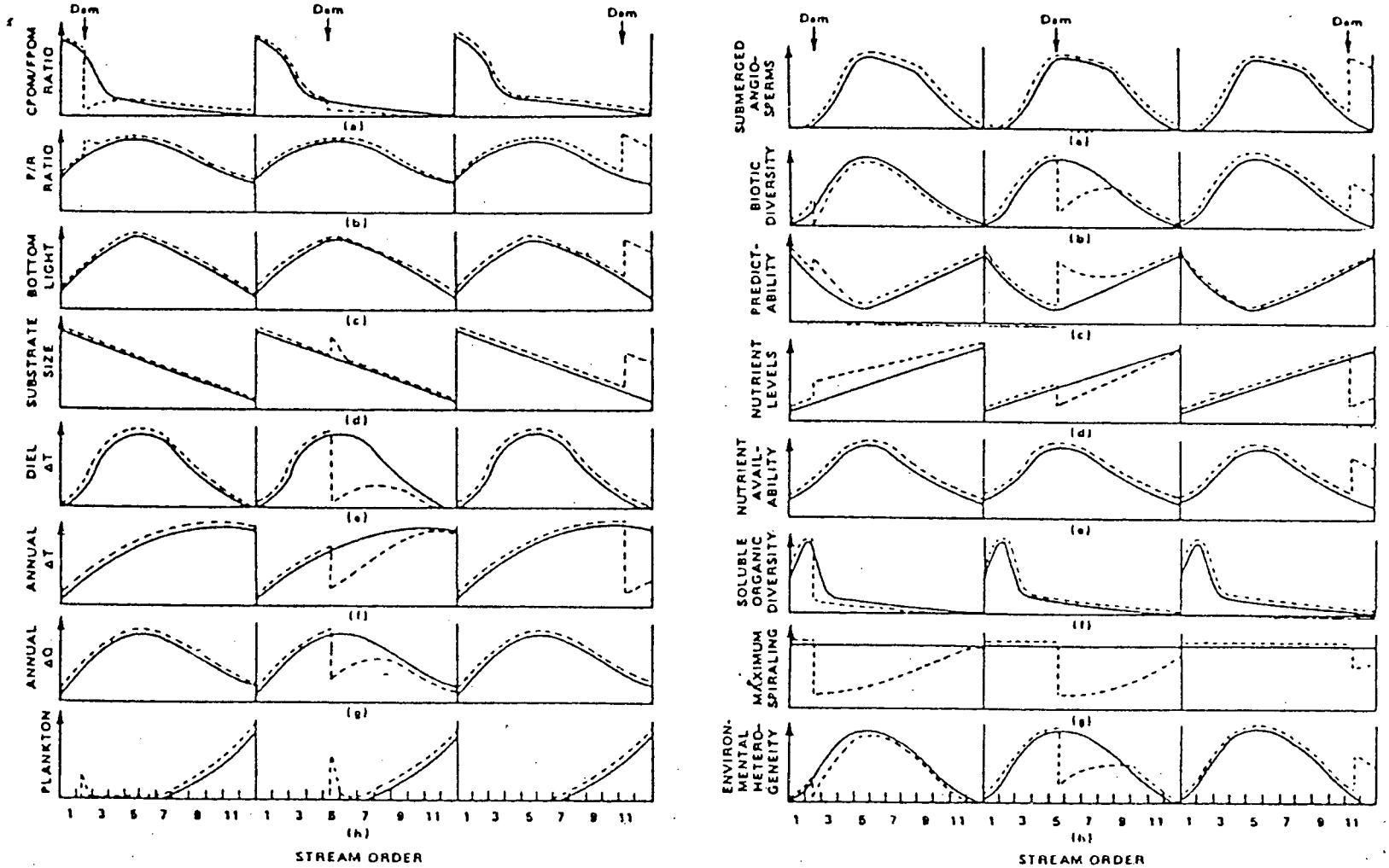

Figure 5: Relative changes in various parameters as a function of stream order based on an interpretation of the natural stream continua theory (solid lines) and postulated effects (dashed lines) of damming headwaters (left column), middle reaches (centre column) and lower reaches (right column) of a river system. From Ward and Stanford (1983a).

to use the term "recovery distance' as a better description of the processes which occur in the receiving reaches of rivers below dams. Therefore, for the purposes of the research reported in this thesis the definition of 'recovery distance' is *that length of stream which is required for any parameter to return to values close to those measured at the inflow to the impoundment or to achieve a new dynamic equilibrium* (Byren and Davies, 1989; O'Keeffe *et al.*, 1990).

The SDC is based on the assumption that both the RCC (Vannote *et al.*, 1981) and the Nutrient Spiralling Hypothesis (Webster, 1975; Webster and Patten, 1979) are conceptually sound and that regulation is the only perturbation experienced by the river. Thus, if a system does not conform to the predictions of the RCC and there are other major disturbances to the system the predictions of the SDC may not apply or may be altered somewhat.

Intermediate Disturbance Hypothesis: The IDH (Ward and Stanford, 1983b) suggests that maximum biotic diversity in streams is maintained by a level of disturbance that is frequent or severe enough to sustain environmental heterogeneity, yet not too frequent or severe to prevent the re-establishment of communities (Figure 6 and Walker, 1985). An intermediate level of disturbance is thought to maintain nonequilibrium conditions that allow the coexistence of a diverse assemblage of species (Ward and Stanford, 1983b).

Ward and Stanford (1983b) postulate that even "undisturbed" or pristine lotic systems are in fact naturally "disturbed", by unpredictable climatic conditions and variability in the supply of essential resources, and that the high biotic diversity of natural streams is, in fact, a function of moderate perturbation. The IDH may account for much of the diversity variance within stream systems and between different types of lotic habitats (Figure 7).

Considerable argument has centred around the general validity of the RCC and its applicability on a global scale, since the cool, temperate, North American streams, on which the concept is based, are likely to be physically, chemically and biologically different from streams elsewhere around the globe (e.g. Winterbourn *et al.*, 1981; Lake *et al.*, 1985; King *et al.*, 1988). The streams on which the RCC and SDC are based are long, 11th order streams whereas, in South Africa the longest river, the Orange River, only reaches 7th order

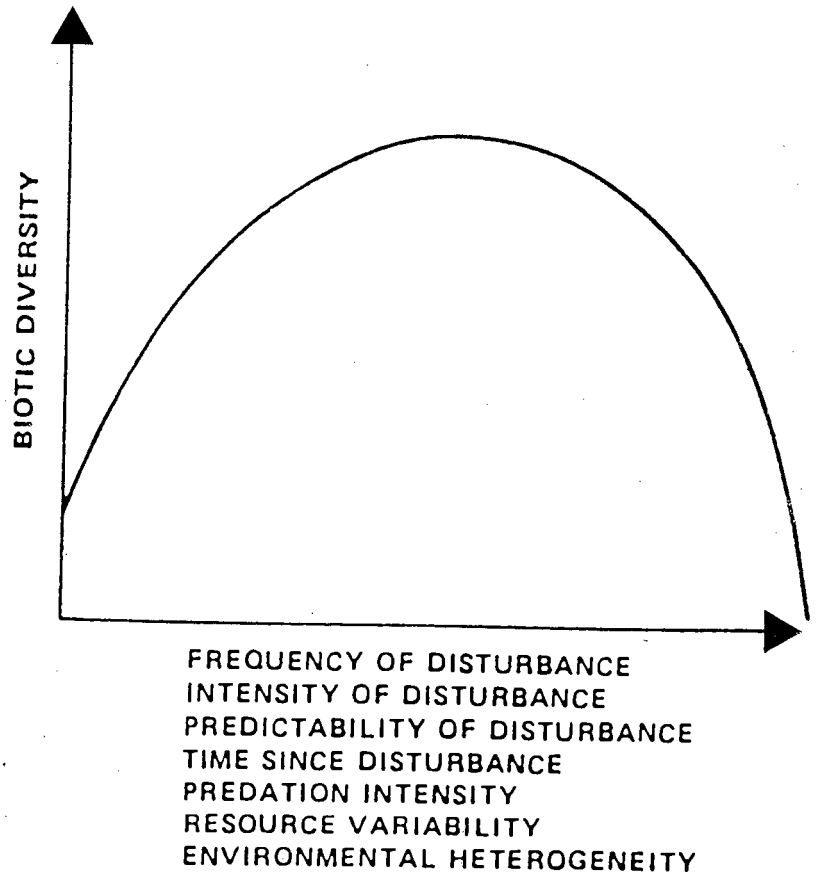

Figure 6: Theoretical relationship between biotic diversity and various measures of "disturbance" (from Ward and Stanford, 1983b; modified from Connell, 1978).

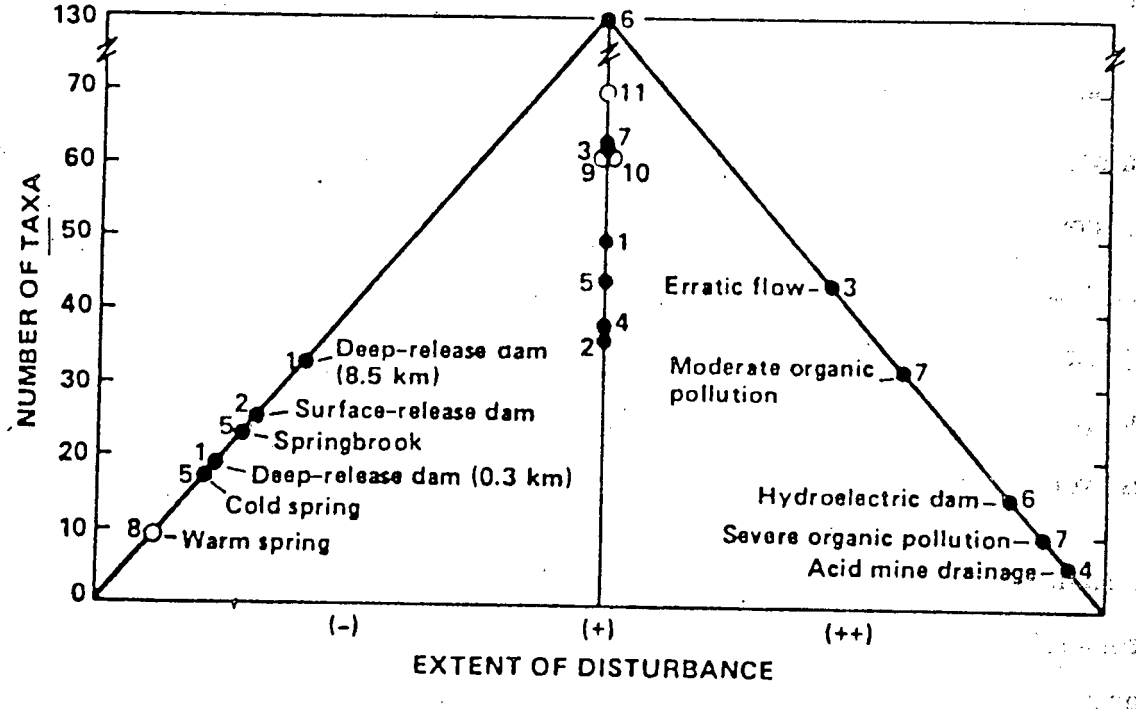

Figure 7: Taxonomic diversity of selected stream macroinvertebrate communities and extent of disturbance (see Figure 2 of Ward and Stanford, 1983b).

and most other systems are 5th or 4th order or less. Walker (1985) has, however, pointed out that any concept may be recast to accommodate different situations. Since the RCC is based on a natural, unperturbed river system, the validity of the RCC in perturbed systems, such as for example an impounded river, may also be questioned (Statzner and Higler, 1985). The RCC may, however, be used as a basis for understanding general trends, and the changes induced by perturbation explained in terms of concepts such as the IDH and the SDC (Ward and Stanford, 1983a,b).

General effects of impoundments on rivers

River regulation may directly or indirectly affect certain characteristics of the stream such as flow, substratum, temperature, water chemistry, aquatic and riparian vegetation, food availability and biotic interactions (Armitage, 1984). The composition and abundance of benthic invertebrate communities are the result of the interplay of these and many other factors. However, factors affecting benthic communities are scale dependant and the distribution and abundance of species are ultimately determined by tolerances to extremes of physical conditions; the harsher the physical conditions, the more directly they affect species distribution (Peckarsky and Dodson, 1980). Flow, temperature and water chemistry have been identified as the most important controlling factors of benthic communities, however (Ward and Stanford, 1979b; Brooker, 1981).

Impoundments can affect downstream flow regimes in four different ways: reduced flow, seasonal flow constancy, increased flow and short term flow fluctuations (Ward, 1976b). The downstream temperature regime can be modified in six main ways (Ward, 1976c; Ward and Stanford, 1979b): (1) increased diel constancy (2) increased seasonal constancy (3) summer depression (4) summer elevation (5) winter elevation (6) thermal pattern change. The degree of modification will depend on the limnological characteristics of the reservoir and the operation (i.e. release pattern and depth) of the dam (Armitage, 1984).

Alterations in water quality owing to river regulation are a function of reservoir basin geomorphology, climate, land-use in the catchment and operation of the dam (Armitage, 1984). Deoxygenation and elevated hydrogen sulphide concentrations are often associated with deep release reservoirs (Hannan, 1979; Davies, 1979), but, in most instances the effects are local and equilibrium is rapid (Armitage, 1984). Oxygen fluctuations in

regulated streams may affect zoobenthos micro-distribution. A reservoir will act as a trap for nutrients, thus hypolimnial releases are nutrient rich, often resulting in increased biotic productivity and diversity (Lowe, 1974; Soltero *et al.*, 1974; Lawson and Rushworth, 1975; Marcus, 1980; Albrecht, 1981).

River regulation affects the natural erosion and transport processes within streams, thus markedly affecting the substratum and hence the biota associated with it. In general, there is a decrease in sediment yield downstream of an impoundment as a result of deposition within the reservoir (Armitage, 1977; Simons, 1979; Grimshaw and Lewin, 1980). The sediment-free water released downstream will "require" a new load of sediment, thus causing bank erosion and bed degradation (Buma and Day, 1977). This alters riparian vegetation and substratum characteristics and thus affects the distribution, composition and abundance of zoobenthos.

Various reviews on the ecological consequences of stream regulation (e.g. Ward, 1982; Armitage, 1984; Ward and Stanford, 1984; Walker, 1985) have drawn together data on specific variables such as water temperature (e.g. Ward and Stanford, 1979b; Marcotte, 1981; Raddum, 1985; Ward, 1985), flow regime (e.g. Ward, 1976c; Brooker and Hemsworth, 1978; Foulger and Petts, 1984) or nutrient levels (e.g. Rada and Wright, 1979; see also Armitage, 1984; Krenkel *et al.*, 1979), and the implications that changes in these variables have for biotic communities, in order to support the SDC. Studies have also been undertaken on the variations in turbidity and suspended solids (e.g. Gray and Ward, 1982; Gilvear and Petts, 1985; Culp *et al.*, 1986; Perry and Sheldon, 1986), alterations in fish populations (e.g. Crisp *et al.*, 1984; Penaz *et al.*, 1968), and changes in invertebrate faunas (e.g. Herlong and Mallin, 1985; Petts and Greenwood, 1985; Munn and Brusven, 1991) downstream of regulating reservoirs. Few studies (e.g. Stanford and Ward, 1984; Gregoire, 1984) have looked at the effect of impoundments on a range of physico-chemical and biotic variables along the entire length of a regulated river and no such studies have been undertaken on acid, blackwater streams in semi-arid, water-stressed climates such as those found in the south-western Cape of South Africa.

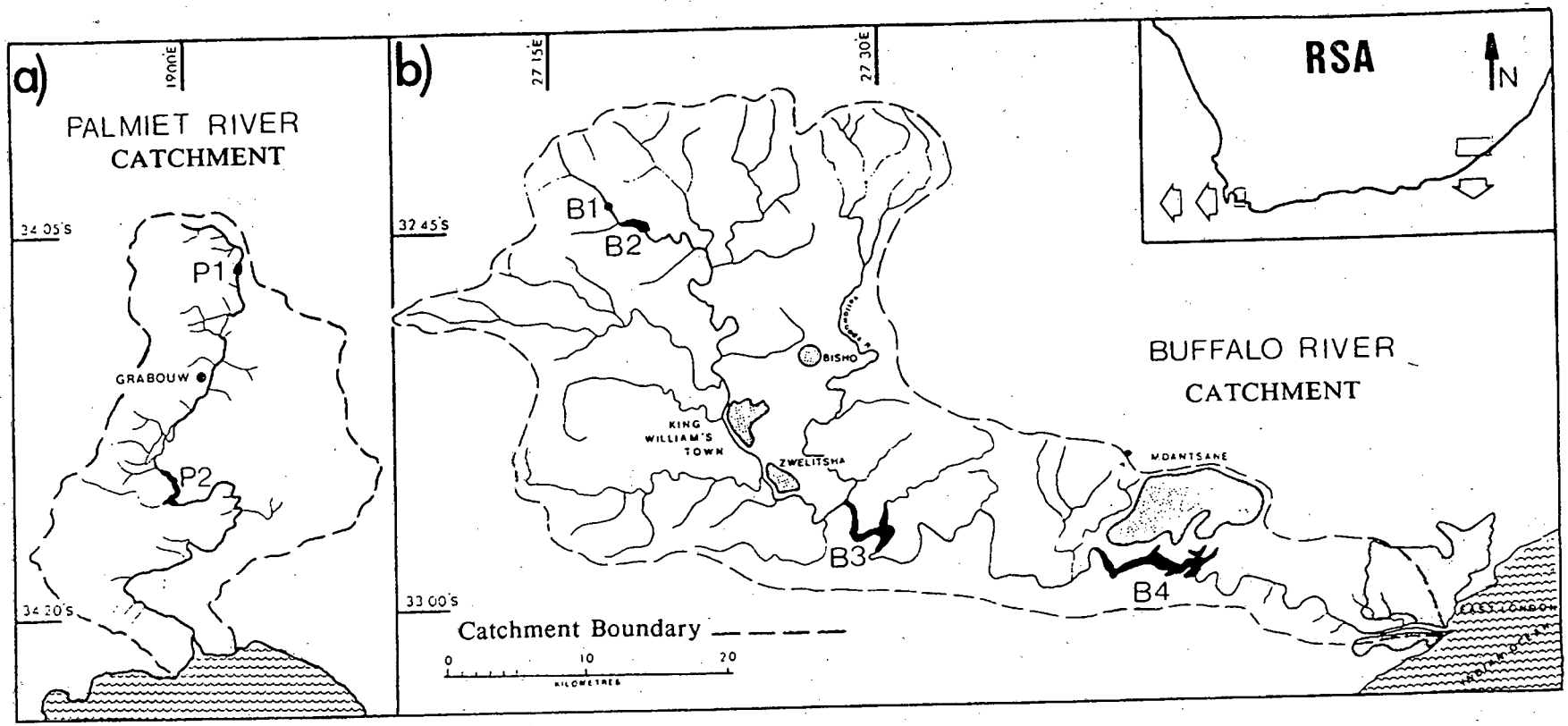

Figure 8: Location of (a) the Palmiet River and (b) the Buffalo River study areas and the position of the dams studied (P1, Nuweberg; P2, Arieskraal; B1, Maden; B2, Rooikrans; B3, Laing; B4, Bridle Drift) (after O'Keeffe *et al.*, 1990)

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STUDY AREA

The flora of the world is divided into six biogeographical kingdoms of which the Cape Floristic Kingdom (largely confined to the Fynbos biome) is the sixth and smallest, covering only approximately 0.04% of the total land surface of the earth and is situated at the southern tip of Africa (Figure 1). The Fynbos Biome stretches in a crescent around the southern tip of Africa and nowhere is it more than 200 km from the sea (Figure 2). The vegetation typically consists of low, fire-adapted, sclerophyllous shrubland, which has counterparts in the macchia of the Mediterranean Basin, the Californian chaparral, the mattoral of Chile and the heathlands or kwongan of southeastern and southwestern Australia (eg. King *et al.*, 1987). The Palmiet River drains a catchment situated at the foot of Africa within the heart of the Fynbos biome (Figure 2).

The quartzitic mountain ranges of the south-western Cape of South Africa, including the catchment of the Palmiet River, are vegetated by mountain fynbos, an exceptionally diverse flora distinguished by the presence of members of the plant families Proteaceae, Ericaceae and Restionaceae (Taylor, 1978). This flora grows on acidic, strongly leached soils where not only are nitrogen and phosphorus in short supply, but where one or more of the other nutrient elements (potassium, sulphur, copper, zinc, molybdenum) may also be limiting (Specht & Moll, 1983). Mountain fynbos is also found in upland plains and valleys where rainfall is sufficiently high to allow the development of moderately to highly leached acid soils on basic rock types such as granite and slates (Lambrechts, 1979; Britton, 1990).

General characteristics of the Palmiet River Catchment

The Palmiet River drains a catchment of approximately 500 km^2, lying between latitudes 34°02' - 34°21' and longitudes 18°53' - 19°10' (Nel, 1980; Clarke, 1989) (Figure 3). The river is 74 km long, with 11 perennial tributaries which have catchment areas greater than 4.5 km^2 (Nel, 1980; Clarke 1989). The river rises in the vicinity of the Landdroskop (1133m AMSL), a peak in the Hottentots Holland Mountain Range (Figure 3). Initially the river flows in an easterly direction, dropping rapidly in altitude over the first few kilometers (Figure 4). About 4 km from its source, the river leaves the steep mountain slopes and swings south towards Grabouw, 12 km away. The river flows down the less steep mountain foothills, dropping about 300 m over the next 9 km to an impoundment, Eikenhof, where

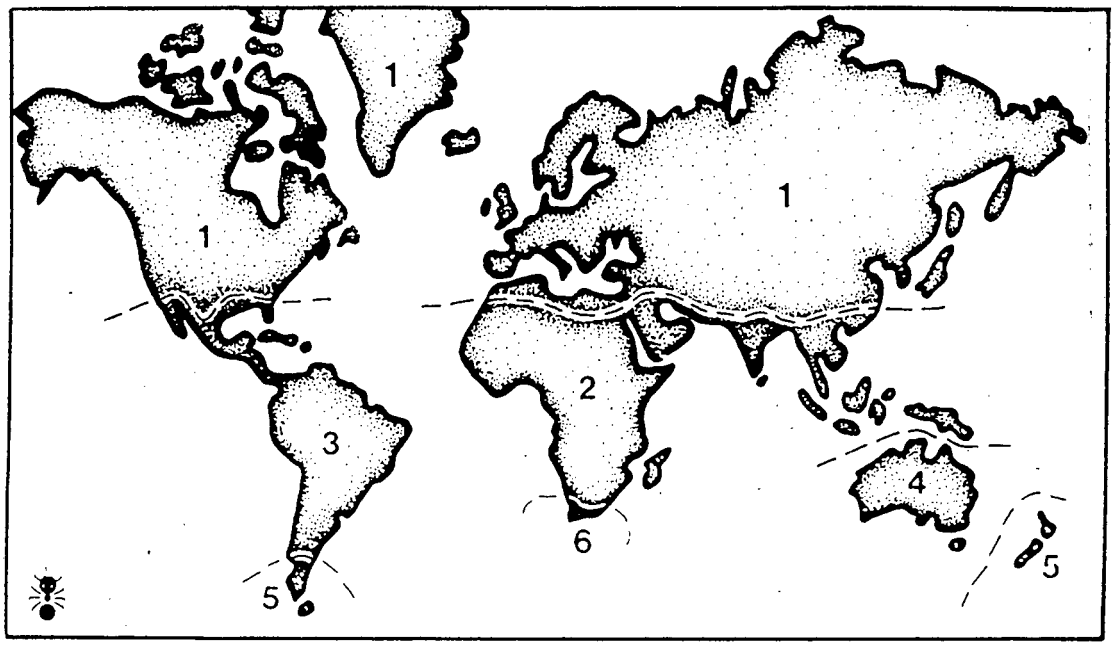

Figure 1: Botanical kingdoms of the world. The key in the top right-hand corner gives the names of, and the percentage of the earths land surface covered by each of the plant kingdoms (from van Rensberg, 1987).

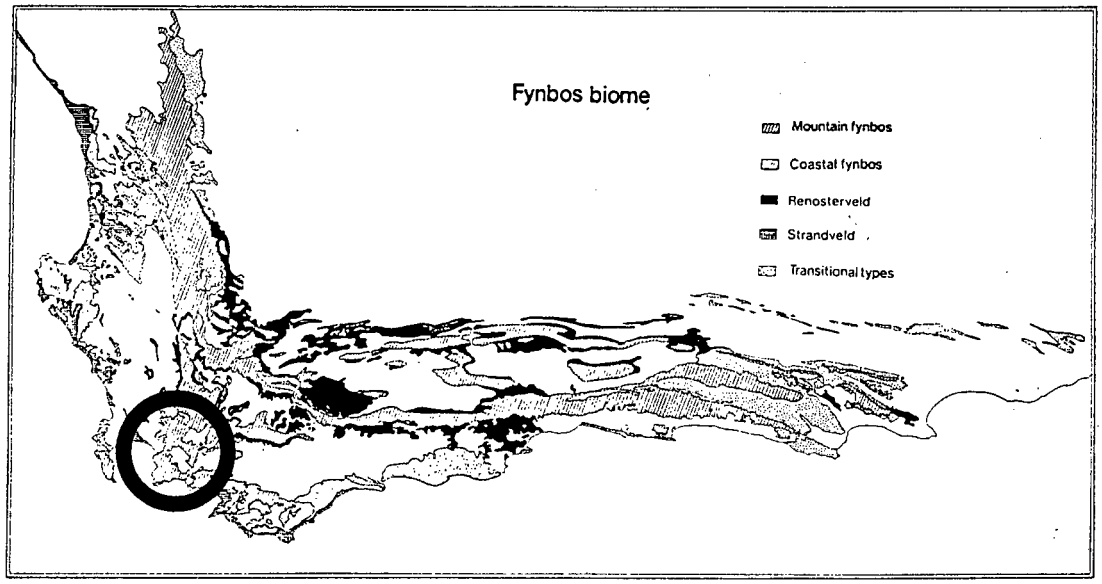

Figure 2: The Fynbos Biome. The Palmiet River catchment lies within the circle (after van Rensberg, 1987).

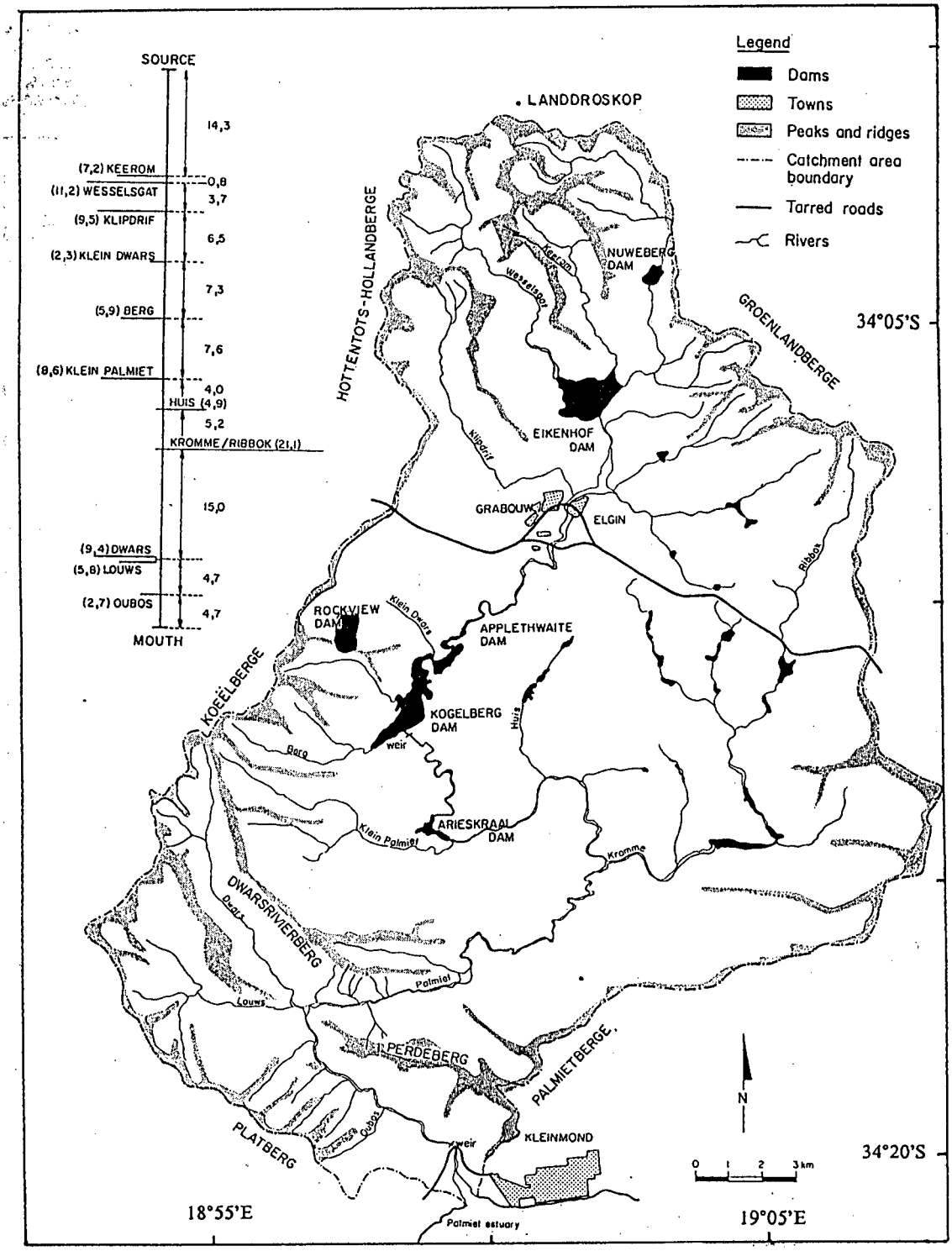

Figure 3: The Palmiet River catchment: Tributaries and topography (after Nel 1980). Only the larger dams on the Palmiet and its major tributaries are shown (after Clarke, 1989). The inset shows the major tributaries, their lengths (in parentheses) and the distances between each one at their point of entry to the Palmiet River.

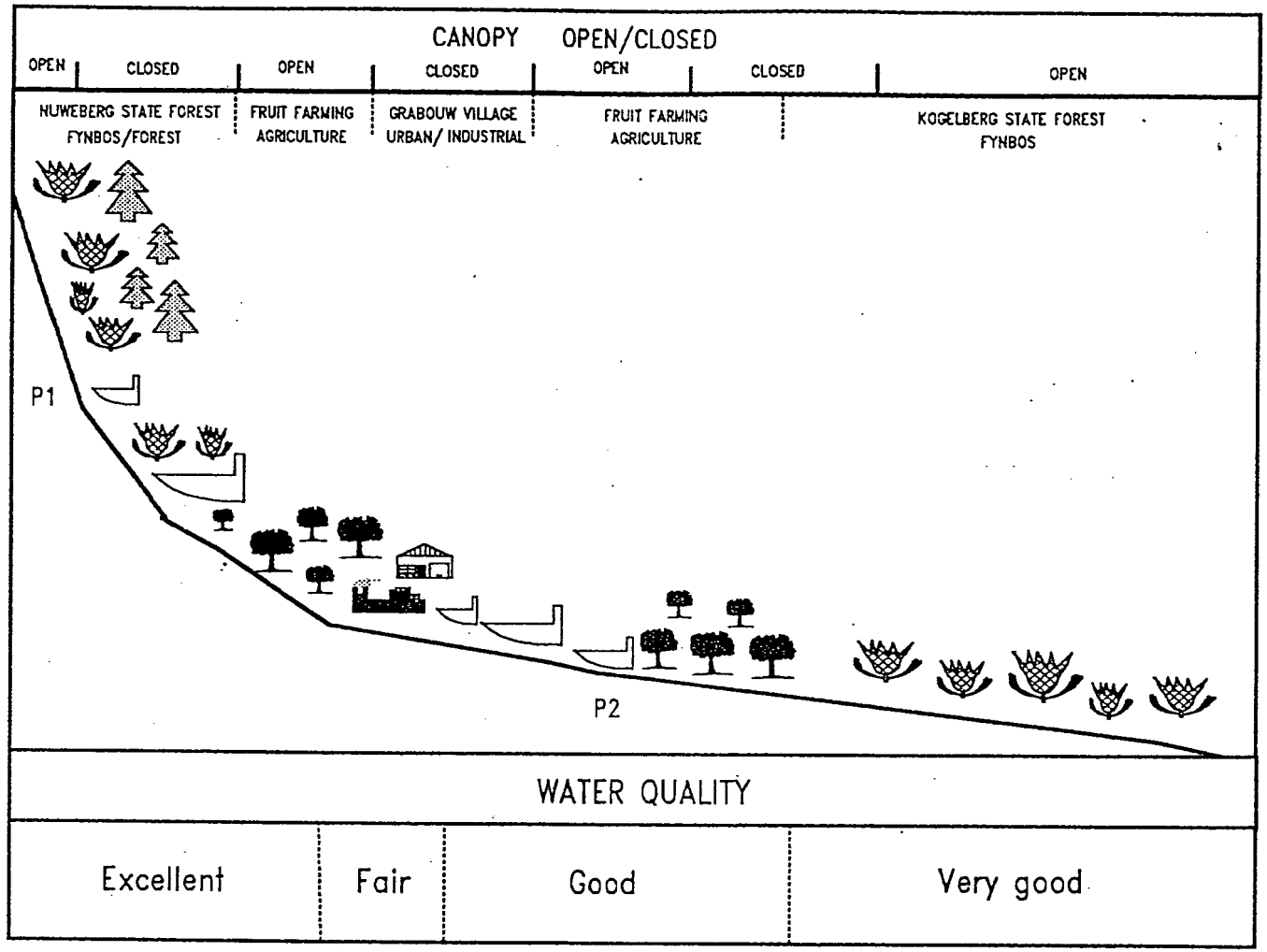

Figure 4:. A schematic vertical profile of the Palmiet River (from Byren & Davies, 1989). The forest referred to in the upper reaches is unnatural pine plantation. P1 = Nuweberg Dam, P2 = Arieskraal Dam.

the river enters the Elgin Valley. From here to the sea the slope is gentle, dropping around 300 m over the remaining 61 km. Below Eikenhof the river flows close to the western boundary of the Elgin Valley for 35 km, flanked by the foothills of the Kogelberg mountains on its west bank. The river flows in a southerly direction until its junction with the Klein Palmiet where it swings north-east for about 6 km before swinging south again. About 16 km from the mouth the river leaves the Elgin Valley and enters the deep valley between the Dwarsrivierberg and Perdeberg mountain ranges. It flows predominantly in a southwesterly direction until the junction with the Louws and Dwars rivers where it swings south-east and heads for the sea. Near the coastal road which traverses the river, the river begins to broaden out into an estuary approximately 1.7 km long. The coastal plain at the mouth is extremely narrow so that the river changes from a mountain stream to an estuary with no intervening stretches typical of a lower river (Clarke, 1989).

The Palmiet River is typical of the geomorphologically 'young' rivers of the Cape (King, 1978; Allanson *et al.*, 1990). The geology of the catchment is dominated by sandstones, quartzites and shales of the Table Mountain Series (TMS) and shales and sandstones of the Bokkeveld Series (Figure 5). Witteberg Series quartzites and shales occur to a lesser extent (Nel 1980). Greater resistance to weathering processes has left TMS as the most prominent feature of the landscape forming high ground and mountain ranges, while the less resistant shales now occur only at the lower elevations. The TMS sandstones are vegetated mainly by Fynbos, whereas the Bokkeveld shales are extensively utilised for agriculture, predominantly fruit farming. The riparian vegetation in this reach consists mainly of alien trees (*Acacia* spp), together with indigenous reeds and emergent aquatic macrophytes, especially *Prionium serratum* (L.f.) Drege ex E. Meyer (the palmiet "reed").

The Palmiet River and its catchment lie within climatic region M (Schultze, 1965), a Mediterranean climate, with a strongly seasonal rainfall. Most rain falls in the austral winter (May-September), and the region is characterised by a warm to hot, dry summer. During the summer months south-easterly to easterly winds predominate, while during the winter north to north-westerly winds prevail (Clarke, 1989). Calm conditions/light variable winds occur throughout the year but predominate during the early winter months (Boucher, 1978). The winter rainfall in the Palmiet catchment area is associated with westerly

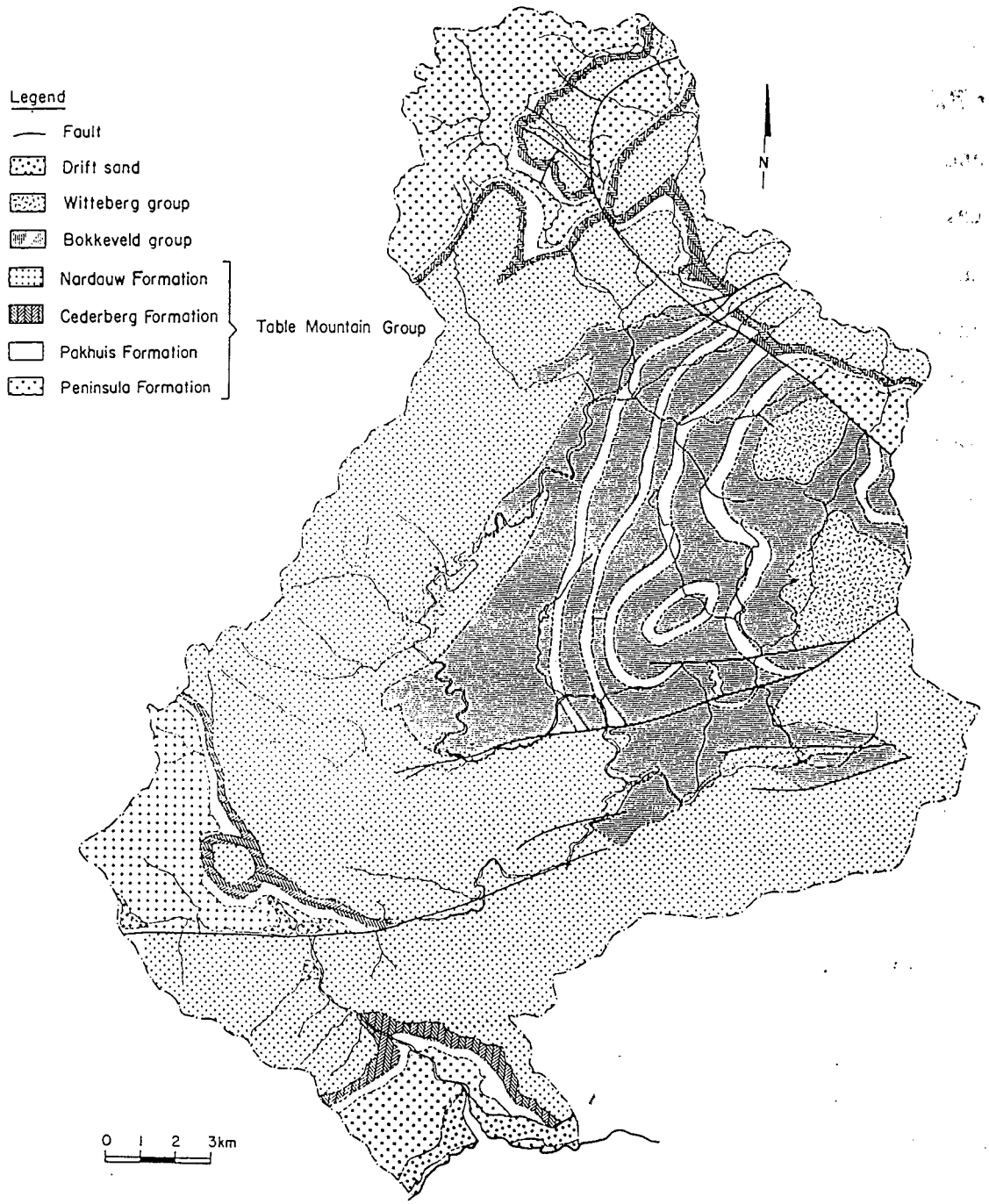

Figure 5: Geological features of the Palmiet River catchment and estuary (from Clarke, 1989).

cyclones which move over the south-western Cape. Orographic rainfall occurs, the mountainous regions receiving more rain than the valleys (Nel, 1980). Rainfall varies from about 700 mm y^{-1} in the low-lying central, eastern and coastal region to around 1500 mm y^{-1} inland. Highest average monthly rainfall generally occurs between June and August, whereas lowest monthly averages occur in December and January. The mean annual rainfall for the entire catchment area is 1139 mm y^{-1} (Nel, 1980). Due to high winds and hot summers, evaporation may reach 1 200 to 1 500 mm y^{-1} in certain places (Branch & Day, 1984). Mist occurs sporadically throughout the year but is most frequent in spring. The lowest average daily minimum and maximum temperatures (-1.9 °C - 23.2 °C) occur during July, while the highest averages (6.6 °C - 34.9 °C) occur during January and February. Due to large differences in elevation, coastal and inland temperatures differ considerably (Nel, 1980). The total mean annual run-off from the catchment is approximately 245 x 10^6 m^3 y^{-1} . Run-off varies considerably on both annual (Figure 6) and monthly (Figure 7) time scales. Between 1963 and 1979, individual annual flow volumes ranged from a minimum of 105 x 10^6 m^3 y^{-1} (1972/3) to a maximum of 422 x 10^6 m^3 y^{-1} (1976/7), highest flow occurring during the period June to September (Department of Water Affairs, S.A., unpubl. data). Generally there is little flow in summer while the highes flow occurs during the period June to September. Peak flow is extremely variable: it can be as little as one-fourteenth of the average monthly run-off and as much as five times greater (Clarke, 1989).

Three main zones can be discerned in the catchment area: near-pristine headwater region, agricultural area (predominantly fruit farming) and the Kogelberg State Forest (KSF: Figure 4). The KSF although a natural mountain catchment reserve, was managed by the South African Department of Forestry and is thus termed a "State Forest". In the pristine headwaters and in the KSF, the dominant vegetation comprises mountain fynbos. The area between the Palmiet and Kromme rivers (Figure 3) is intensively cultivated. Apples form the main crop and other deciduous fruits such as pears and peaches are also grown but are of minor importance (Nel, 1980). The rest of the catchments area lies within the boundaries of State Forests where several pine plantations have been established. Cultivated lands and plantations comprise approximately 55% of the catchment area. The remaining 45% is covered by fynbos (Nel, 1980).

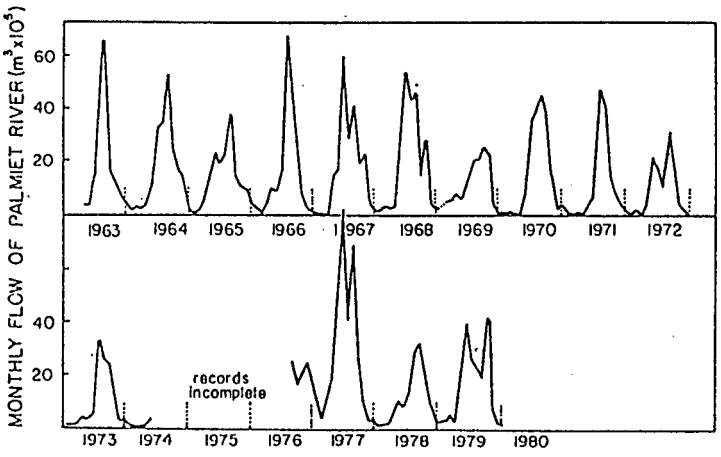

Figure 6: Annual flow volume for the Palmiet River (from Clarke, 1989).

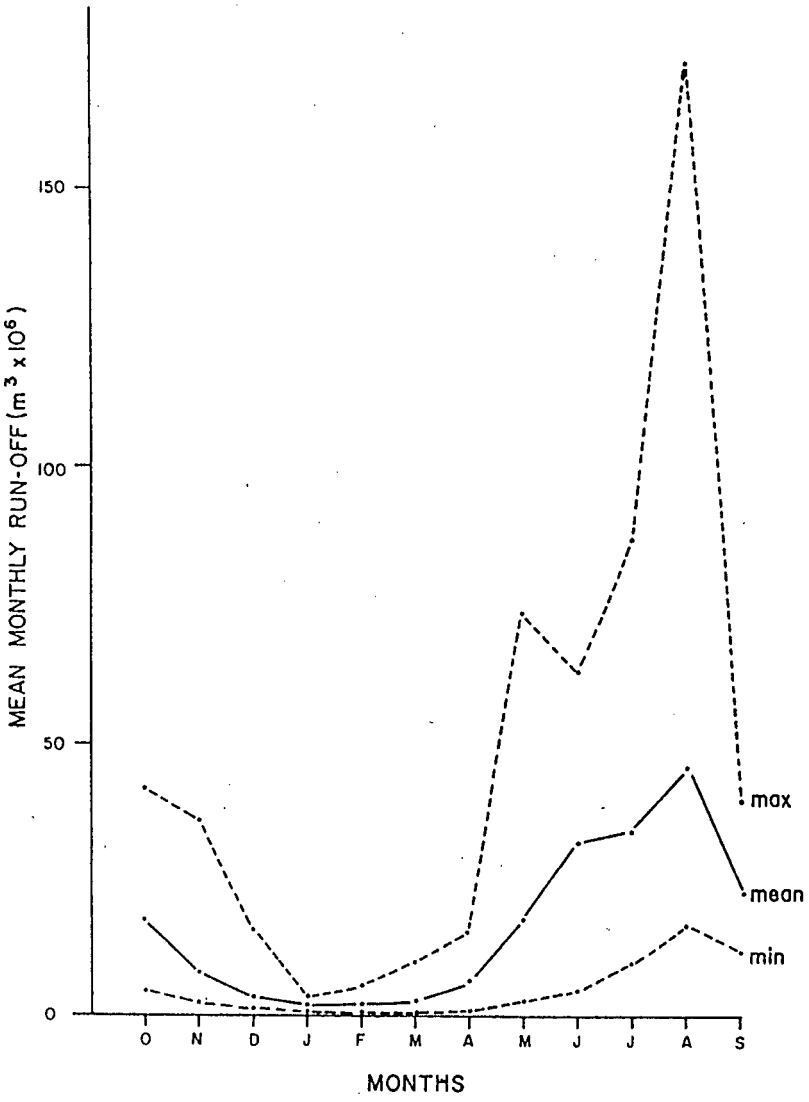

Figure 7: Monthly flow volume for the Palmiet River (from Clarke, 1989).

The river is impounded at five points within the first 40 km and then runs freely to the estuary which lies between Betty's Bay and Kleinmond (Figure 3). Four of the impoundments act as irrigation storages, listed in order downstream: Nuweberg (built in 1971, capacity 3.9 X 10^6 m^3), Eikenhof (built in 1977, capacity 22.7 X 10^6 m^3), Applethwaite (built in 1952, capacity 3.3 X 10^6 m^3) and Arieskraal (built in 1967, capacity 5.9 X 10^6 m^3) (Table 1). A fifth impoundment, Kogelberg (built 1987, capacity 19 X 10^6 m^3), together with an off-stream rockfill reservoir, Rockview, comprise the Palmiet Pumped Storage Scheme. This system, which is used to generate electricity, came "on line" in April 1987. Between the Nuweberg and Kogelberg State Forests the tributaries of the Palmiet River, the Kromme and Huis Rivers, and their tributaries, are extensively impounded to form small reservoirs, mainly for irrigation purposes (Figure 3).

Table 1: Characteristics of the five dams along the length of the Palmiet River.

	Nuweberg	Eikenhof	Applethwaite	Kogelberg	Arieskraal
maximum capacity (x$10^6$$m^3$)	3.8	22	3.3	19	5.9
release depth	bottom	bottom	surface	middle	bottom
distance (km) from source	6	12	21	25	31
Altitude (m AMSL)	510	340	250	210	200
wall type/ height	earth-fill/ *ca* 20 m	concrete/ 35 m	concrete/ ?	concrete/ 46 m	concrete 26 m
use	holding	irrigation supply	irrigation supply	pumped storage	irrigation supply
operation	on demand	on demand	winter overspill	on demand	constant release

Sampling sites

Eleven sites were chosen down the length of the river (Figure 8), largely concentrated in two zones: one below the upper-reach impoundment, Nuweberg, and one below the middle reach impoundment, Arieskraal, as they provided reasonable lengths of downstream reaches (7 km and 37 km, respectively) over which recovery distances could be investigated. The sites chosen were: the pristine upper reaches, PR1 (Plate 1; Figure 9); above Nuweberg, PR2 (Plate 2; Figure 10); immediately below the bottom release of Nuweberg, PR3

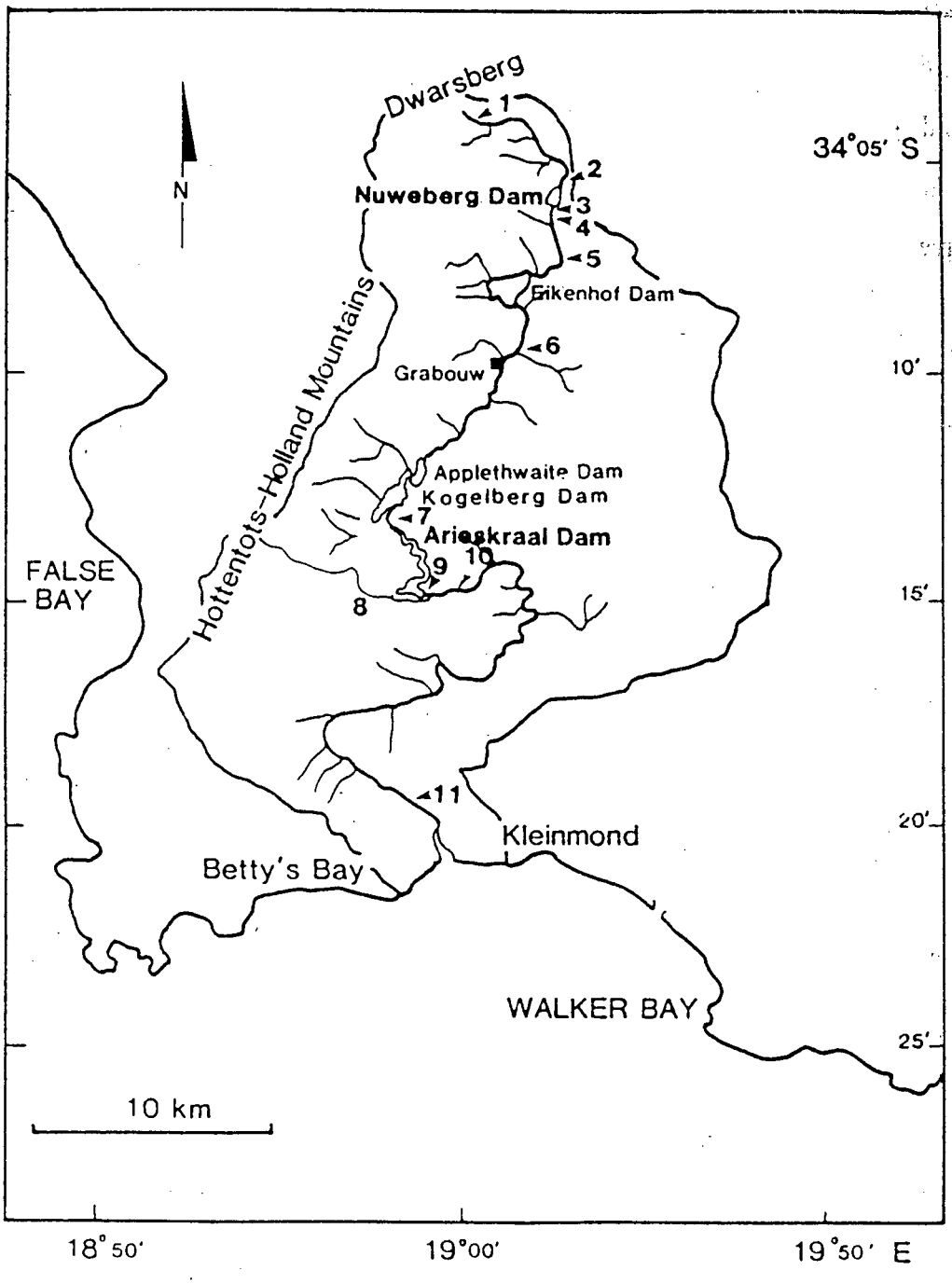

Figure 8: Map showing the location of the sampling sites on the Palmiet River (after Byren and Davies, 1989).

(Plates 3 & 4; Figure 11); 0.5 km below Nuweberg, PR4 (Plate 5; Figure 12); 3 km below Nuweberg, PR5 (Plate 6; Figure 13); a site in the village of Grabouw, PR6 (Plate 7); below Kogelberg and above Arieskraal, PR7 (Plates 8 & 9; Figure 14); a site, PR8 (Plate 10; Figure 15), on the Klein Palmiet, a tributary from which water is directly abstracted into Arieskraal; immediately below the bottom release of Arieskraal, PR9 (Plates 11 & 12; Figure 16); 3 km below Arieskraal, PR10 (Plate 13; Figure 17); and 30 km below Arieskraal, just above the estuary, PR11 (Plate 14; Figure 18).

Plates 1 to 14 give pictoral representation of the sites and Figures 9 to 18 show the profile of the river bed at each site during low flow (dotted line) and high flow (solid line).

Table 2: Study sites and a brief description of their characteristics

SITE	DESCRIPTION	WIDTH (range in m)	FLOW ($m^3 s^{-1}$) median	minimum
PR1	pristine headwaters, boulders	1-8	0.1672	0.0045
PR2	above Nuweberg, gravel	2-24	0.2236	0.0282
PR3	below Nuweberg, rocky	2.5-3.5	0.3417	0.1646
PR4	*ca* 500 m below Nuweberg, rock, bridge	8-9	0.4107	0.1370
PR5	*ca* 3 km below Nuweberg, weir, rocky	2-9	0.1738	0.0861
PR6	in the village of Grabouw		not measured	
PR7	above Arieskraal, below Kogelberg, weir, rock & gravel	3-7	1.2254	0.0533
PR8	tributary, Klein Palmiet, water abstracted to Arieskraal, stony	23-45	1.8338	0.3171
PR9	below Arieskraal,boulders	14-16	0.9085	0.3257
PR10	*ca* 3 km below Arieskraal, boulders	8-12	2.0317	0.3545
PR11	*ca* 3 km above estuary, boulders	11-20	3.0783	0.5929

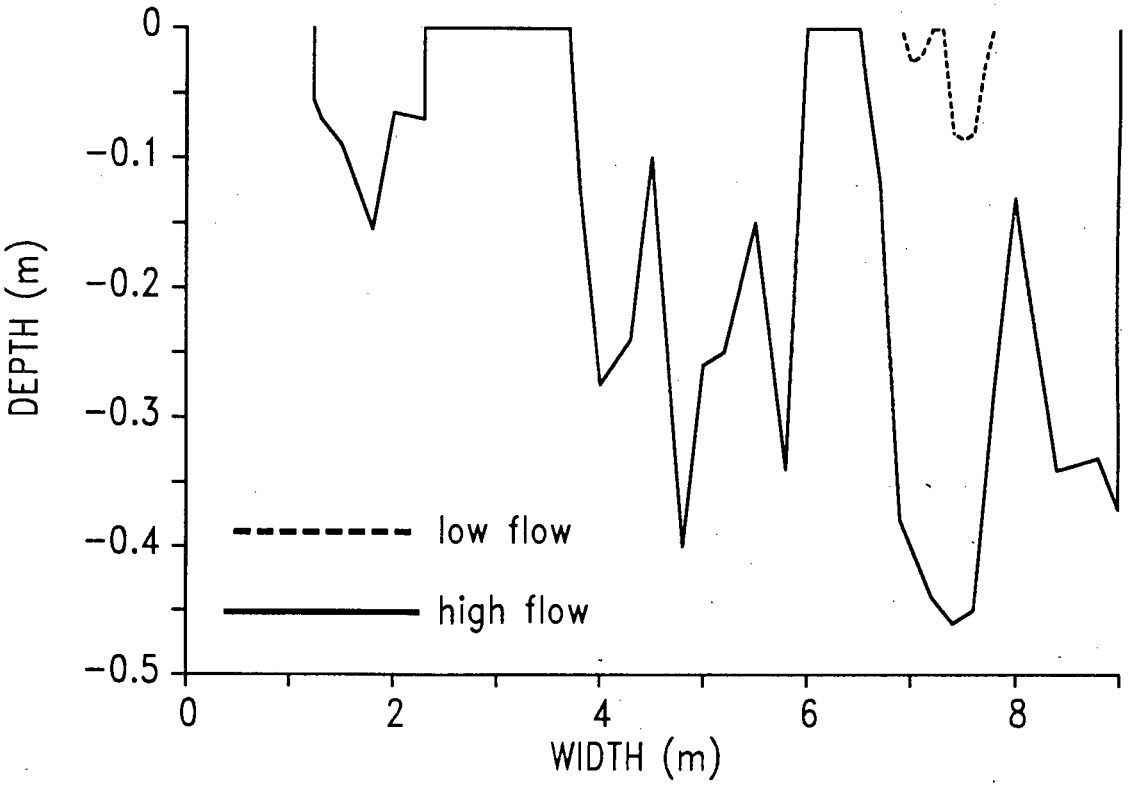

Figure 9: Site PR1: The profile of the river bed from left to right looking downstream during low (dotted line) and high (solid line) flow conditions.

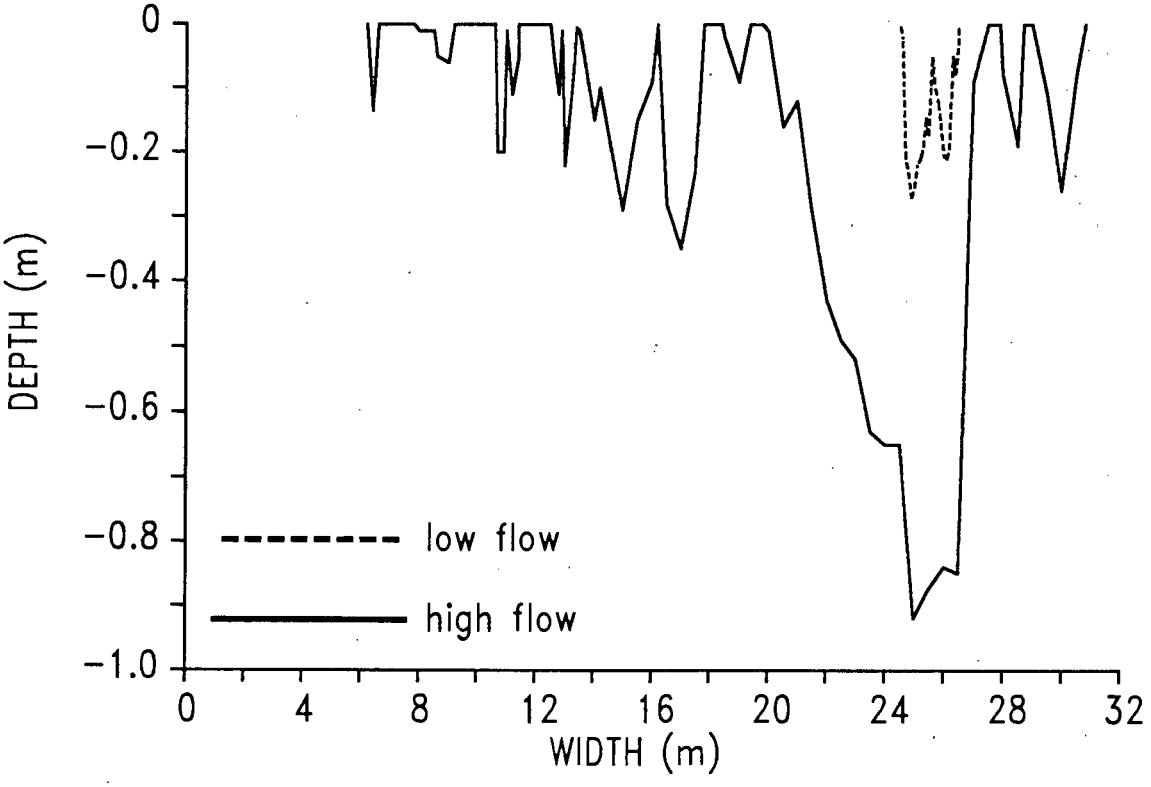

Figure 10: Site PR2: The profile of the river bed from left to right looking downstream during low (dotted line) and high (solid line) flow conditions.

Plate 1: Site PR1, the pristine headwaters.

Plate 2: Site PR2, immediately above Nuweberg Dam

Plate 3: The bottom-release outflow from Nuweberg Dam.

Plate 4: Site PR3 immediately below the outflow from Nuweberg Dam.

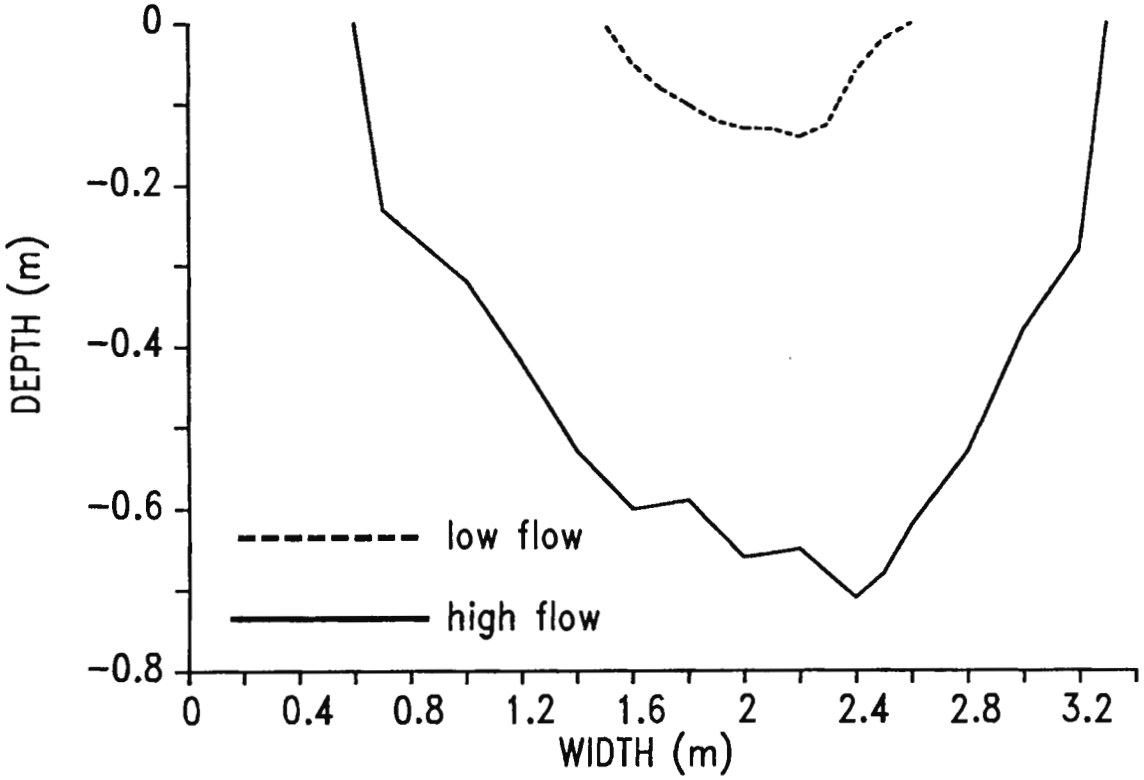

Figure 11: Site PR3: The profile of the river bed from left to right looking downstream during low (dotted line) and high (solid line) flow conditions.

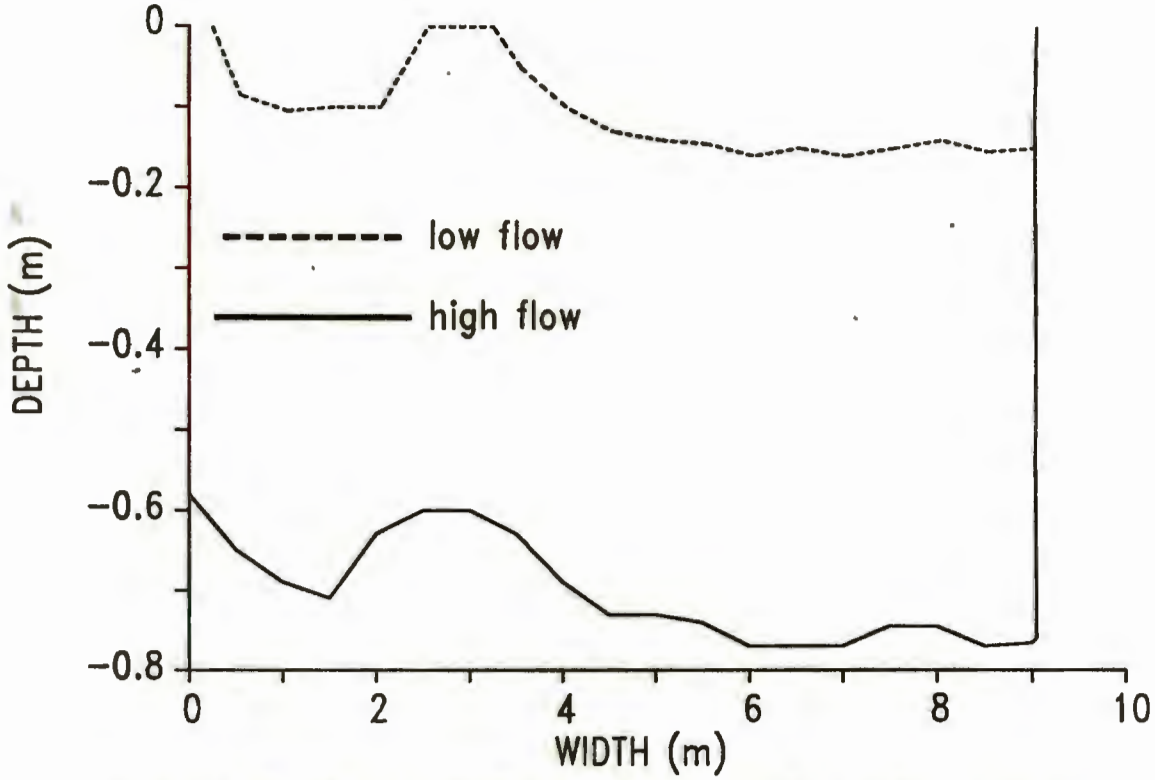

Figure 12: Site PR4: The profile of the river bed from left to right looking downstream during low (dotted line) and high (solid line) flow conditions.

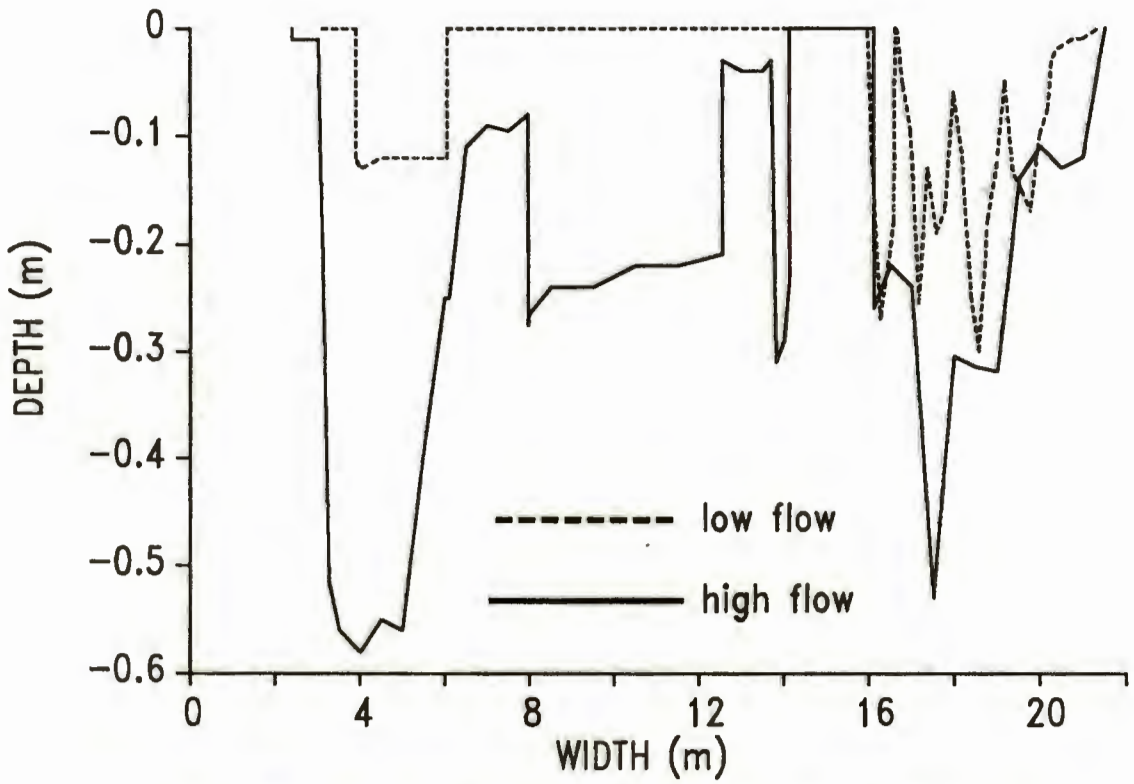

Figure 13: Site PR5: The profile of the river bed from left to right looking downstream during low (dotted line) and high (solid line) flow conditions.

Plate 5: Site PR4, *ca* 0.5 km below Nuweberg Dam

Plate 6: Site PR5, *ca* 3 km below Nuweberg Dam.

Plate 7: Site PR6, as the river flows through the villiage of Grabouw.

Plate 8: The Kogelberg Dam under construction, immediately upstream of site PR7.

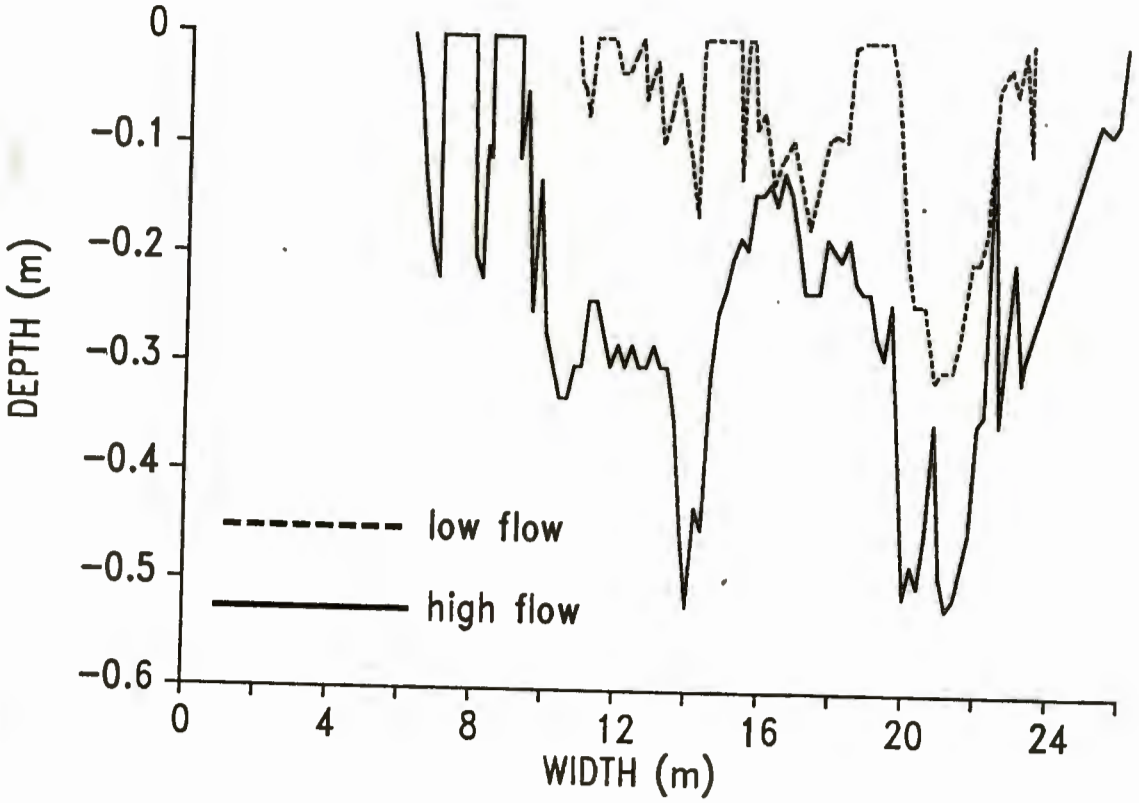

Figure 14: Site PR7: The profile of the river bed from left to right looking downstream during low (dotted line) and high (solid line) flow conditions.

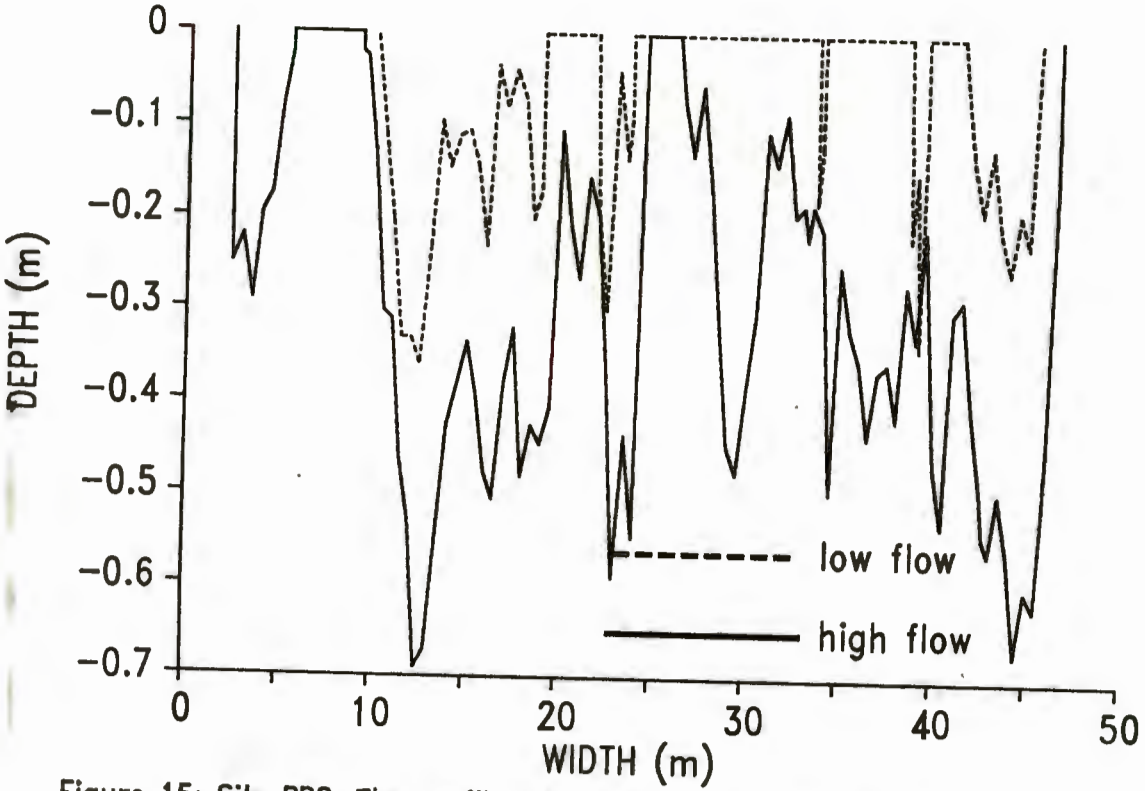

Figure 15: Site PR8: The profile of the river bed from left to right looking downstream during low (dotted line) and high (solid line) flow conditions.

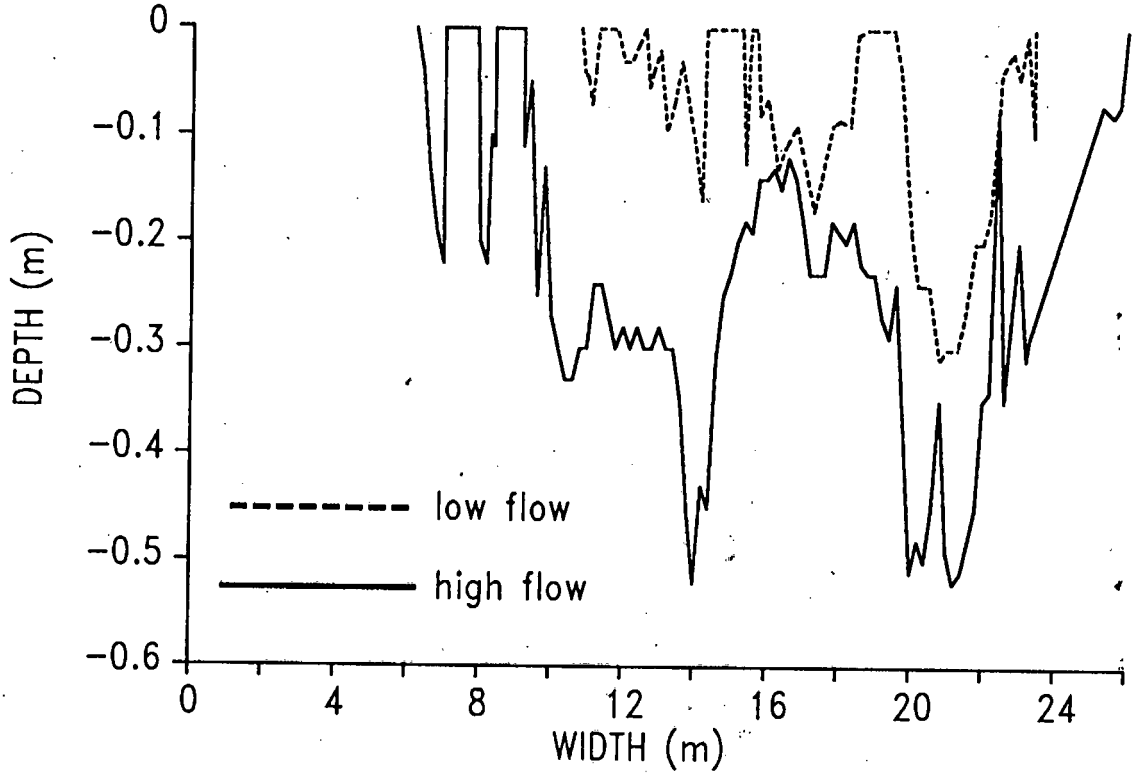

Figure 14: Site PR7: The profile of the river bed from left to right looking downstream during low (dotted line) and high (solid line) flow conditions.

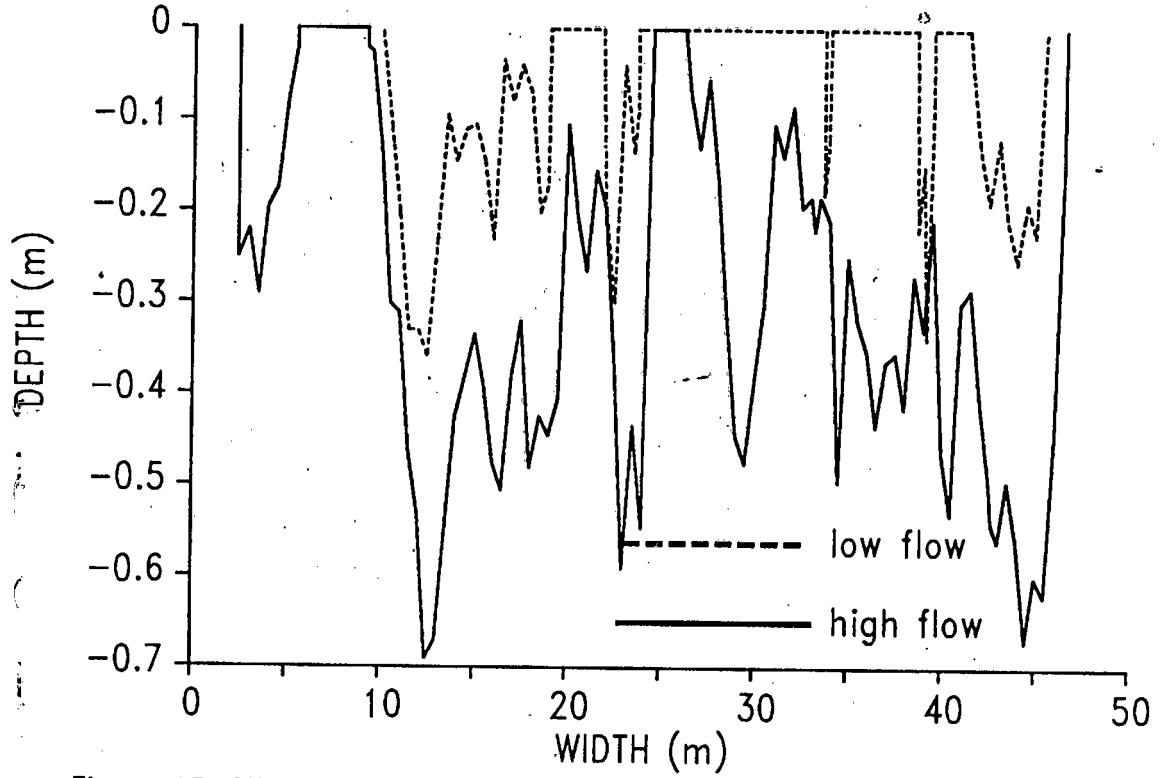

Figure 15: Site PR8: The profile of the river bed from left to right looking downstream during low (dotted line) and high (solid line) flow conditions.

Plate 9: Site PR7, immediately upstream of Arieskraal Dam.

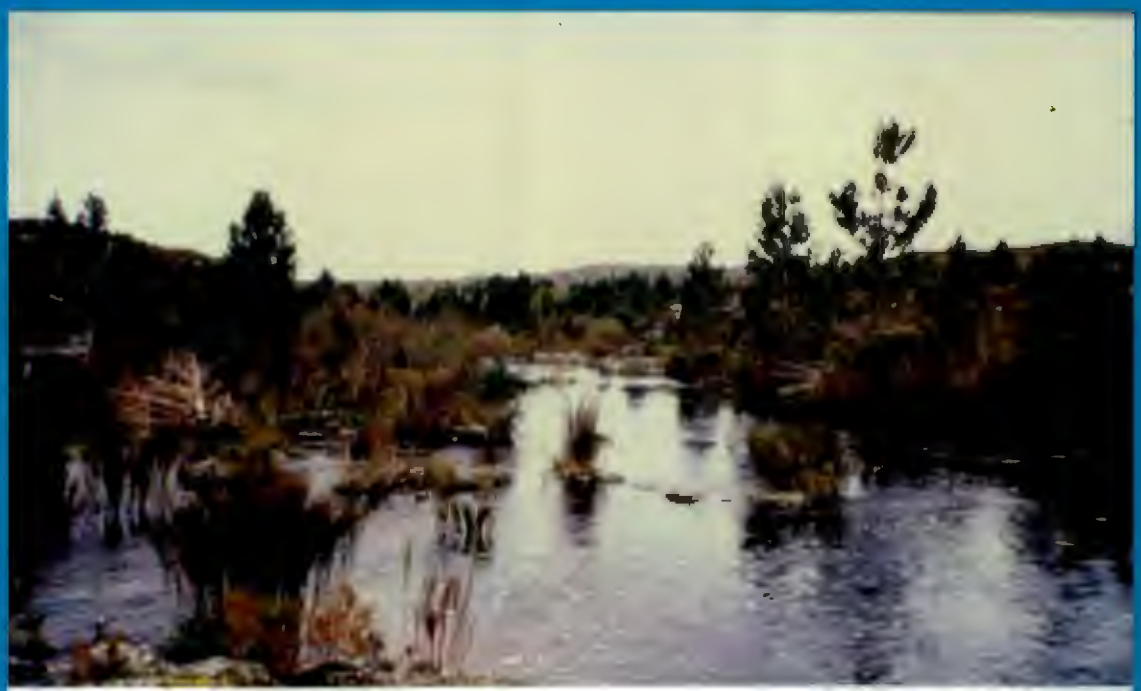

Plate 10: Site PR8, the pristine tributary, the Klein Palmiet.

Plate 11: Arieskraal Dam and spillway in action.

Plate 12: Site PR9, immediately below the bottom-release of Arieskraal Dam.

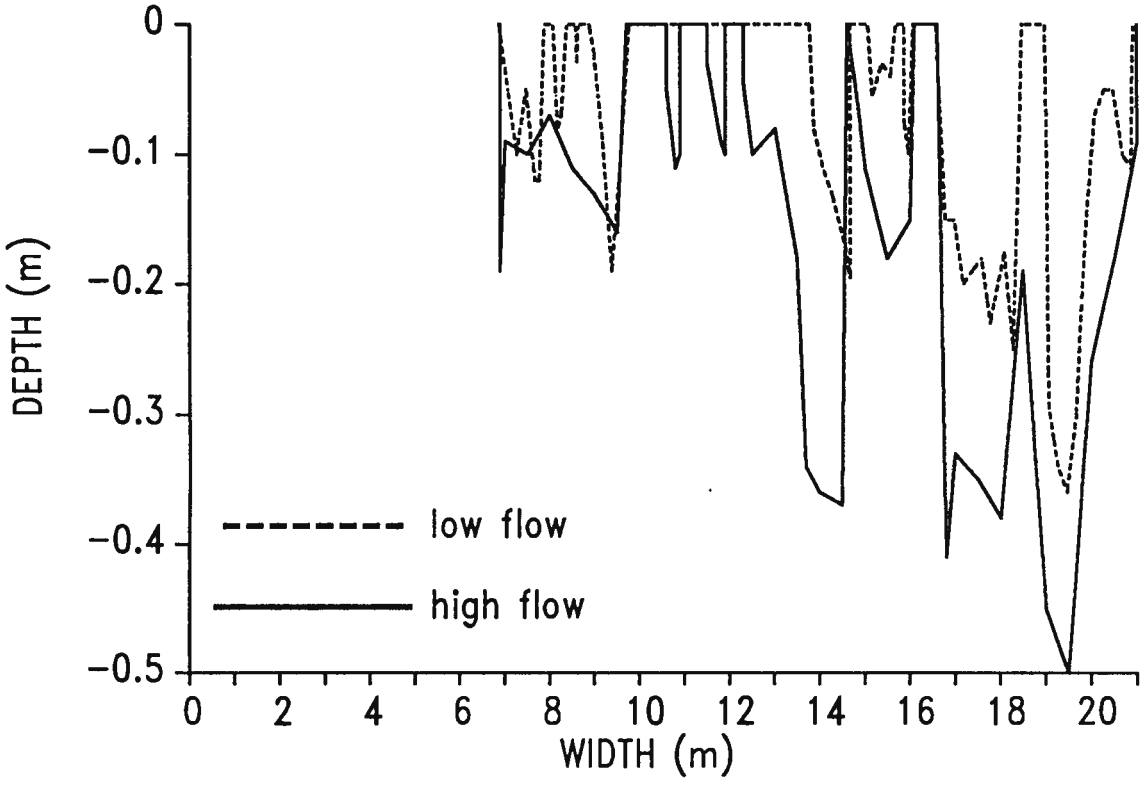

Figure 16: Site PR9: The profile of the river bed from left to right looking downstream during low (dotted line) and high (solid line) flow conditions.

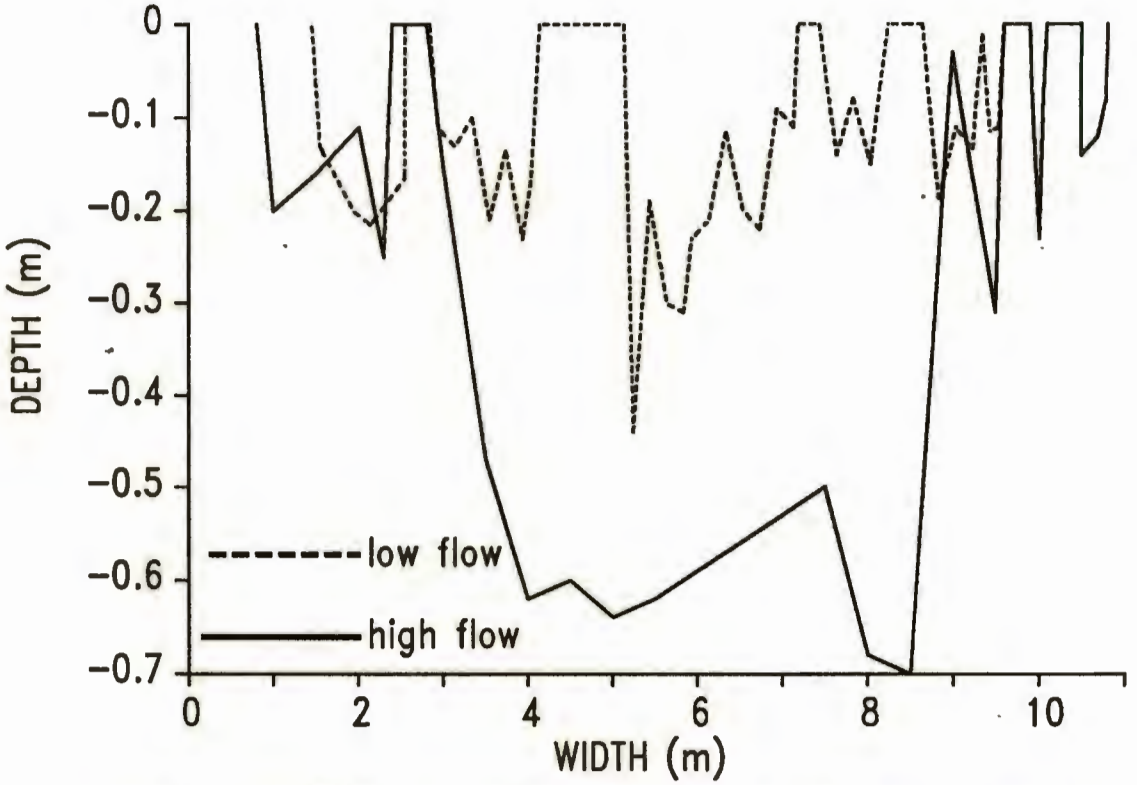

Figure 17: Site PR10: The profile of the river bed from left to right looking downstream during low (dotted line) and high (solid line) flow conditions.

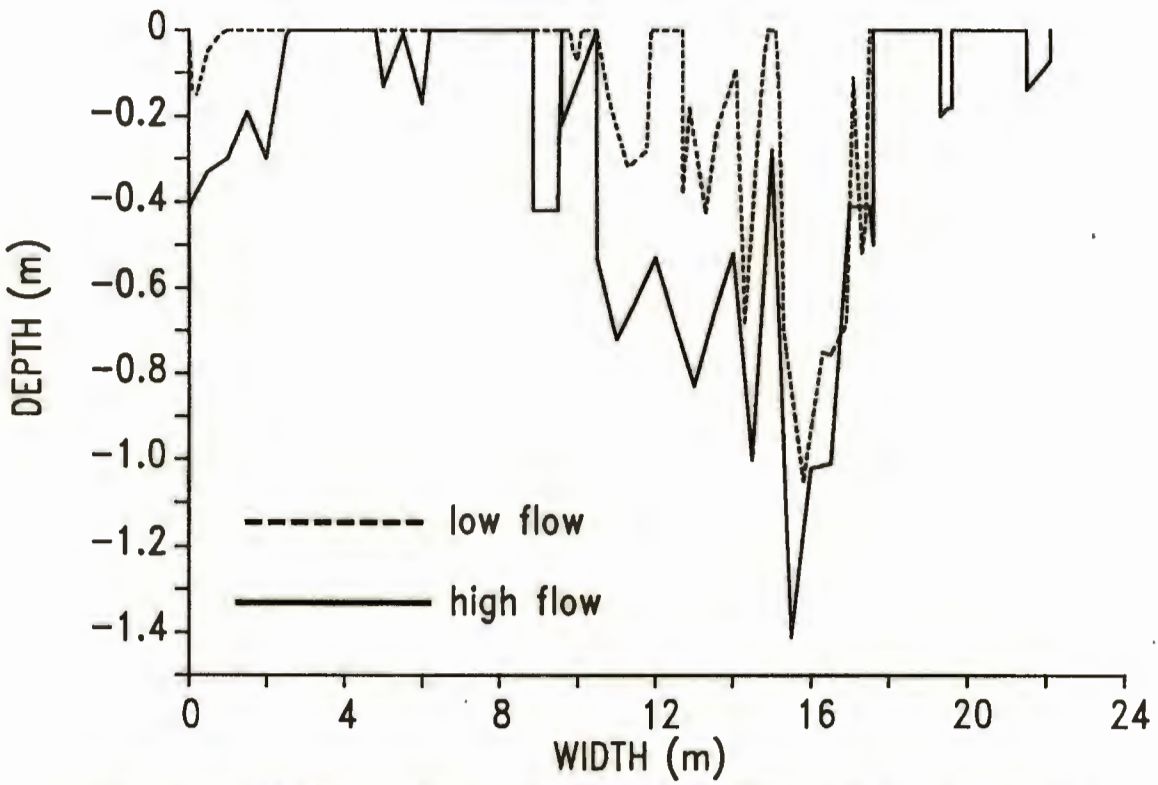

Figure 18: Site PR11: The profile of the river bed from left to right looking downstream during low (dotted line) and high (solid line) flow conditions.

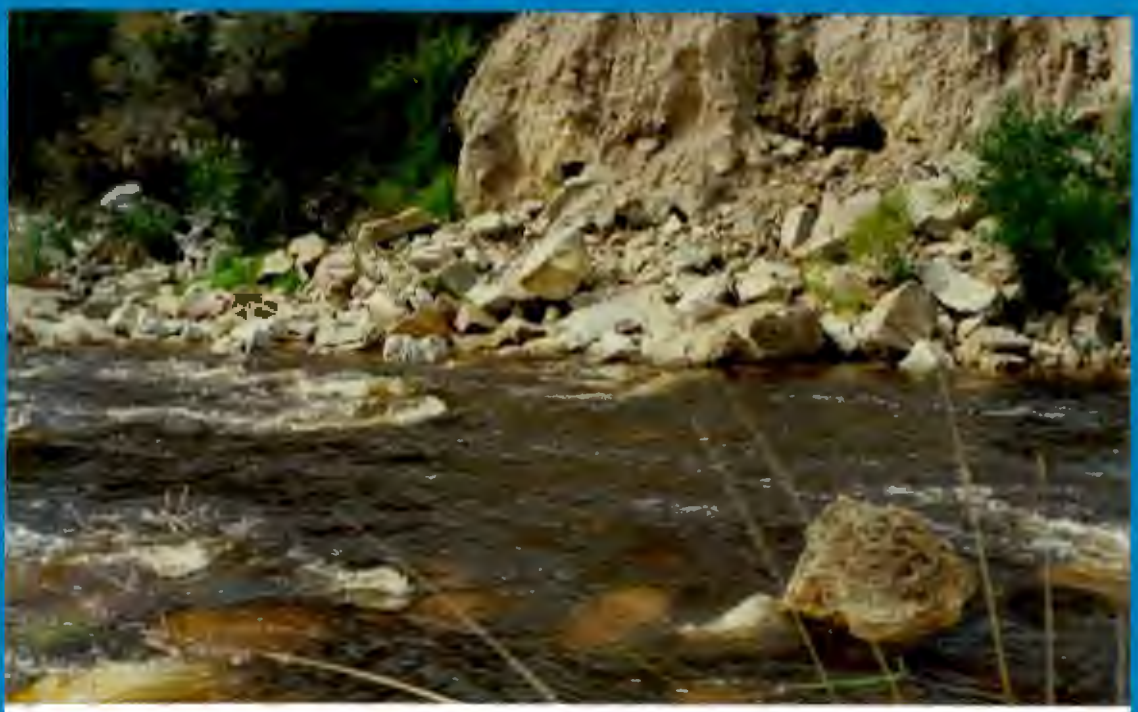

Plate 13: Site PR10, *ca* 3 km below Arieskraal Dam.

Plate 14: Site PR11, 30 km below Arieskraal and 3 km above the estuary.

Plate 15: The 19th hole - overnight stop.

Sampling and analytical methods

Sampling was undertaken monthly from February 1986 to April 1988, a total of 26 months sampled. In order to sample all eleven sites each month sampling occurred over two days with an overnight stop in the mountains near Arieskraal (Plate 15). Temperature, dissolved oxygen, pH and conductivity were measured on site. Water for chemical analysis, total suspended solids (TSS) and total dissolved solids (TDS) was pre-filtered through an 80 μm-mesh net and then filtered through pre-weighed, pre-combusted, Whatman GF/F filters which capture particles down to a size of 0.7 μm. The filter was stored for further TSS analysis. The filtrate was bottled in polythene containers pre-cleaned in 5% Extran^R solution (phosphate-free) and double-distilled water, frozen on dry ice and returned to the laboratory for analysis. The various measurements taken and the methods used are detailed below:

a) Field Measurements

1)	Temperature:	Mercury thermometer, accurate to $\pm$0.5 °C
2)	Dissolved Oxygen:	YSI Dissolved Oxygen meter, accurate to $\pm$0.2 mg l^{-1}
3)	pH:	Lilliput field pH meter, accurate to 0.1 pH units
4)	Conductivity:	Crison CDTM-523 field meter, temperature corrected to 25 °C, accurate to 0.1 μS cm^{-1}
5)	Current velocity:	Ott C2 field current meter
6)	Profile:	depth every 20 cm across river width

b) Calculations

Discharge was calculated using the following method:

A specific stream cross-section was chosen at each site and marked to be used on each sampling occasion. The stream width was measured and at certain intervals (different at each site) across the profile flow rate was measured using the Ott C2 current meter. The discharge for each section of the profile was calculated from the equation:

$$\text{Discharge } (m^3\ s^{-1}) = \text{Current velocity } (m\ s^{-1}) \times \text{Area } (m^2)$$

The total discharge passing the chosen point of cross-section was thus the sum of the discharges for each section of the profile.

c) *Laboratory Analyses*

1) Total Suspended Solids (TSS): a known volume of water was filtered through a pre-weighed, pre-combusted, Whatman GF/F filter, dried at 60 °C for 48 h and re-weighed. The organic fraction was calculated by weight difference after combustion at 480 °C for 2 h. Weighing was done on a Sartorius precision laboratory balance accurate to 1 mg. All measurements are expressed as mg l^{-1} .

2) Total Dissolved Solids (TDS): a known volume of water (400 ml), filtered through a Whatman GF/F filter, was evaporated at 90 °C from pre-weighed glass beakers. The beakers were re-weighed and the difference calculated. Weighing was done on a Sartorius precision laboratory balance accurate to 1 mg. Results are expressed as mg l^{-1}.

3) Total Alkalinity: determined by the titrimetric method of Golterman *et al.* (1978), using 0.001 M HCl to a mixed indicator end-point and expressed as mg l^{-1} $CaCO_3$. The precision is estimated at 2-10% at total alkalinity between 1 and 0.1 mmol l^{-1}.

4) Chloride: samples were titrated with $HgCl_2$ to a diphenylcarbozone-bromphenol blue mixed indicator end-point (Golterman *et al.*, 1978) and expressed as mg l^{-1} Cl^-. Precision is estimated at 0.5 mg l^{-1} from 0-50 mg l^{-1} .

5) Sulphates: analysed spectrophotometrically using a methylthymol blue-barium chloride colour reagent after the sample had been passed slowly through an amberlite ion-exchange column. Once a calibration curve, using Na_2SO_4 standards, had been set up for the colour reagent, the sample concentrations were determined from the calibration curve and expressed as mg l^{-1} $SO_4^=$. Precision is estimated at 0.1 mg l^{-1} in a 200 ml sample.

6) Nutrients: nitrates, nitrites, phosphates, ammonium and dissolved carbon were determined using a Technikon Auto Analyser Method (Mostert, 1983) and expressed in $\mu g\ l^{-1}$ of the nutrient atom (e.g. NO_2-N, NO_3-N, NH_4-N or PO_4-P). For nitrates the standard deviation of the mean is $\pm$ 0.26 at the level of 15 μg at. NO_3^- -N l^{-1} , for ammonia the standard deviation of the mean is $\pm$ 0.06

at the level of 2.5 μg at. NH_4^+-N l^{-1} and for phosphates the standard deviation of the mean is $\pm$ 0.04 at the level of 1.5 μg at. P l^{-1} .

7) Suspended particulate transport and macroinvertebrate drift: an 80 μm-mesh plankton net with a mouth area of 0.048 m^2 was immersed in the flowing river water for a known period of time (usually 5 minutes), and the flow through the mouth of the net measured with the Ott C2 current meter. The drifting particles, both organic and inorganic were collected and fixed with 4% formalin in fresh water. In the laboratory the samples were preserved with 1% phenoxitol, separated into three size fractions (>950 μm, 950-250 μm and 250-80 μm), and sorted. The animals were removed, identified, counted and weighed to determine species composition and biomass. The remaining particulates were dried, weighed and combusted to determine the organic and inorganic proportions of the coarse and fine suspended particulate matter. Weighing was done on a Sartorius precision laboratory balance accurate to 1 mg. Since the study involved sampling an entire catchment, manpower and time constraints prohibited an in-depth study of diel drift patterns. The 5-10 minute drift samples were sufficient for a determination of transported particulate matter and the faunal drift information was thus a bonus giving an indication of day-time, background drift patterns.

8) Benthic macroinvertebrates: "Stones in current" (*sensu* Chutter 1968) were sampled using a 0.1 m^2 modified box sampler (King *et al.*, 1988), with the sediment stirred to a depth of *ca* 10 cm. Three separate samples were taken at each site, fixed with 4% formalin in fresh water and returned to the laboratory. The samples were preserved with 1% phenoxitol, split into size fractions and sorted as for the drift above.

9) Lake Plankton: Samples were taken at different depths within the two reservoirs by lowering an 8 *l* Nissen bottle on a rope (marked at half meter intervals) to the required depth (top, middle and bottom) and closing it with a metal messenger. In order to obtain enough material 4 bottles (32 *l*) were taken at each site. The

samples were fixed with 4% formalin in fresh water and returned to the laboratory where they were preserved in 1% phenoxitol and the entire sample sorted, identified and counted.

d) Multivariate Analysis:

1) TWINSPAN: Two-way indicator species analysis (TWINSPAN) (Cornell Ecological Programs 41: Hill, 1979) arranges sites into two distinct groups along the first axis of a reciprocal averaging ordination. Further divisions are achieved using the presence, absence and relative abundance of indicator species, and species are classified as well as samples (Palmer, 1991). The TWINSPAN programme first constructs a classification of the samples, and then uses this classification to obtain a classification of the species according to their ecological preferences. The two classifications are then used together to obtain an ordered two-way table that expresses the species' synecological relationships as succinctly as possible (Hill, 1979).

   To quote "TWINSPAN makes its dichotomies by dividing ordinations in half. There are three ordinations involved:

   1. The primary ordination (reciprocal averaging), which is divided to obtain an initial, crude dichotomy;
   2. The refined ordination, which is derived from the primary ordination through the identification of differential species; and
   3. The indicator ordination, based on a few of the most highly preferential species.

   The refined ordination is normally used to determine the dichotomy. The indicator ordination is essentially an appendage, put there for the convenience of users who want a succinct characterisation of the dichotomy." (Hill, 1979).

2) CANOCO: CANOCO, a FORTRAN programme for canonical community ordination by partial, detrended or canonical correspondence analysis, principle components analysis and redundancy analysis, developed by Cajo J. F. Ter Braak (1987), was used to analyse the lake and benthic data and to interrelate them with environmental variables. The Canonical ordination technique (Canonical

Correspondence Analysis or CCA) was chosen as the method which best described the results obtained. This is a multivariate, direct gradient, analysis technique, which attempts to explain the species and sample responses by ordination axes that are linear combinations of environmental variables (Ter Braak, 1987). This results in an ordination diagramme, known as a biplot, in which points represent species and sites, and vectors represent environmental gradients (Ter Braak, 1986). The position of the head of the arrow for each environmental variable depends on the eigen values (importance measure of an ordination axis; Ter Braak, 1987) of the axes, and the intraset correlations of that variable with the axes. By connecting the origin of the plot (the centroid of the site points) with each of the arrow heads, the arrows representing the variables are obtained. The length of a vector representing a variable is equal to the rate of change in the weighted average as inferred from the biplot, and is therefore a measure of how much the species distributions differ for that variable. The more important the variable, the longer the arrow. The ordination diagramme with environmental variable vectors, which determine a direction or axis, can be interpreted by extending the vector in both directions and dropping a perpendicular from each species point to this axis. The endpoints of the perpendicular indicate the relative positions of the centres of species distributions along the axis. The species endpoint which is furthest along the vector in the direction of the arrow has the strongest relationship with that specific variable (Ter Braak, 1986). The approximate ranking of the weighted averages for a particular variable can be seen easily from the order of the endpoints of the perpendiculars of the species along the axis for that variable (Ter Braak, 1986). Further, the origin of the plot is the grand mean of each variable and the inferred weighted average is higher than the mean if the species endpoint lies on the same side of the origin as the head of an arrow, and is lower than average if the origin lies between the endpoint and the head of the arrow (Ter Braak, 1986).

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THE EFFECT OF STREAM REGULATION ON THE PHYSICO-CHEMICAL PROPERTIES OF THE PALMIET RIVER, SOUTH AFRICA.

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Note: The author was actively involved in all aspects of the project including the initial planning, the sampling and anlyses and the bulk of the written work for this manuscript. This paper was co-authored by the supervisor, who provided financial and field assistance and critical assessment of the manuscript.

REGULATED RIVERS: RESEARCH & MANAGEMENT, VOL. 3, 107–121 (1989)

THE EFFECT OF STREAM REGULATION ON THE PHYSICO-CHEMICAL PROPERTIES OF THE PALMIET RIVER, SOUTH AFRICA

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ABSTRACT

The effect of regulation, by multiple impoundment, on 'discontinuity' (recovery) 'distances' (*sensu* Ward and Stanford, 1983) for various physico-chemical attributes of the Palmiet River (a short, steep gradient, cool temperate, acid, low-nutrient system) was investigated. Physico-chemical features were measured monthly, from February 1986 to August 1987, at 11 sites along the river, but concentrating on two zones: one below an upper-reach impoundment, Nuweberg Dam, and one below a middle-reach impoundment, Arieskraal Dam. Median total suspended solids, nitrates, nitrites and ammonium all increased below both dams with varying levels of 'recovery'. Median spot temperatures, pH and alkalinity increased below Nuweberg, but decreased below Arieskraal Dam, whereas the converse was true for soluble reactive phosphate. Nuweberg had no effect on conductivity and total dissolved solids, while Arieskraal caused a slight decrease. The river remained well oxygenated down its length.

Distinct seasonal variations were recorded for: flow rate, with flow reversal below Nuweberg and flow constancy below Arieskraal; temperature, with seasonal shifts and dampening of annual temperature range below both dams; alkalinity, with seasonal shifts below Arieskraal, and nitrites and nitrates, but not for any other attributes. At least partial recovery was noted in all cases, but in some instances, recovery was incomplete to the estuary. The implications of such alterations, for invertebrates, in terms of reduction in habitat diversity as well as for food supply must be considerable and studies are currently under way to determine community structure and diversity.

KEY WORDS Serial discontinuity concept Recovery distances Seasonal shifts Flow Temperature Alkalinity pH Nutrients Blackwater Acid stream

INTRODUCTION

Lotic ecologists have only recently begun to recognize the modifications engendered by stream regulation on downstream reaches, but despite the relatively short time, the literature is expanding rapidly (*vide* for example, the volumes by Ward and Stanford, 1979a; Lillehammer and Saltveit, 1984; Petts, 1984; Craig and Kemper, 1987). Dams may affect many components of lotic ecosystem functioning: flow (e.g. Foulger and Petts, 1984; Cowx *et al.*, 1987; Hadley *et al.*, 1987); temperature (e.g. Ward and Stanford, 1979b; Marcotte, 1981; Raddum, 1985; Ward, 1985; Cowx *et al.*, 1987; Webb and Walling, 1988); sediment regimes (e.g. Gilvear and Petts, 1985; Gilvear, 1988; Petts, 1988); channel morphology (e.g. Simons, 1979; Hadley *et al.*, 1987; Harvey and Watson, 1988); water chemistry (e.g. Krenkel *et al.*, 1979; Rada and Wright, 1979), and biotic community structure and functioning (e.g. Ward and Stanford, 1979b; Armitage, 1984). All of these impacts will vary according to reservoir characteristics and the release patterns adopted by managers (e.g. Ward and Stanford, 1979a, 1983; Ward, 1985).

A number of important hypotheses and concepts have been developed during the past decade, some of which have direct bearing on understanding the impacts of river regulation. For example, the River Continuum Concept (RCC) of Vannote *et al.* (1980) views lotic systems in terms of biological adjustments predictably structured along a longitudinal resource gradient, with downstream communities dependent on processing by upstream communities.

The Nutrient Spiralling Hypothesis (NSH) maintains that nutrients move downstream in a helical fashion as they alternate between organic (bound) and inorganic (free) phases, rather than remaining in a

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closed cycle (e.g. Webster, 1975; Webster and Patten, 1979). The Serial Discontinuity Concept (SDC) of Ward and Stanford (1983) interprets impoundment as an interruption of the longitudinal gradients predicted by the RCC, with the resultant discontinuity in biotic and abiotic trends requiring a 'recovery distance' to 'reset' after the perturbation. The SDC predicts that the effects of impoundment are a function of the *position* of the dam along the longitudinal stream profile (Ward and Stanford, 1983). Further, the SDC implicitly assumes that both the RCC and the NSH are conceptually sound. Consequently the regulated stream may provide a testing ground for these ecological theories (Ward and Stanford, 1984). One of the major concerns, however, centres on the general validity of the RCC and a number of recent papers have criticized the concept as being inapplicable on a global scale (e.g. Winterbourn *et al.*, 1981; Lake *et al.*, 1985; King *et al.*, 1988). However, Walker (1985) has commented that in general, a concept may be recast to accommodate different situations.

South African stream ecosystems are facing increasing stresses caused by over-utilization of water in a water-stressed region (Alexander, 1985). Owing to the geomorphology of the land mass, rivers provide almost all of the water supply for a rapidly expanding population, and almost every permanent stream is now regulated either singly or multiply by impoundments (Department of Water Affairs, 1986). Multiple storages have been constructed for hydroelectric power production, potable domestic consumption, industrial uses, and agriculture, and the idea of 'recovery' from discontinuities caused by dams has assumed importance amongst the scientific and management communities in that it may provide a tool for the rational management of regulated lotic systems. Research into ecological functioning using such approaches may well assist future design of dams and alter their operation.

Few studies of river regulation (Grégoire and Champeau, 1984; Stanford and Ward, 1984) have looked at entire river systems with multiple impoundments, and none have concentrated on stream regulation impacts on physico-chemical features along the length of a river. This paper describes the results of a programme designed to determine the regulation effects of multiple impoundment on 'recovery distances' for various physico-chemical parameters in the Palmiet River, western Cape, South Africa—a short, steep-gradient, cool temperate, acid, clear, low-nutrient system. This study was undertaken in tandem with a study of the Buffalo River in the eastern Cape (a long, shallow gradient, warm, neutral to alkaline, turbid and high-nutrient system) carried out by the Institute for Freshwater Studies, Rhodes University, and the two studies are being used to generate comparative data for management (e.g. O'Keeffe *et al.*, submitted).

O'Keeffe *et al.* (submitted) have discussed the problems surrounding the concept of discontinuity distances (e.g. pre-impoundment conditions should ideally be known before measurements of discontinuity can be attempted), and accepting their arguments, we have preferred to use the term 'recovery distance' as a better description of the processes which occur in the receiving reaches of rivers below dams. As no pre-impoundment data were available for our system, we have taken 'recovery distance' to be *that length of stream which is required for any parameter to return to values close to those measured at the inflow to the impoundment, or to achieve a new dynamic equilibrium* (O'Keeffe *et al.*, submitted).

STUDY AREA

The Palmiet River drains a catchment of approximately 500 km^2, lying between latitudes 34°02′–34°21′ and longitudes 18°53′–19°10′ (Nel, 1980; Clarke, in press) (Figure 1). The system is approximately 74 km long, with 11 perennial tributaries which have catchment areas greater than 4 km^2 (Nel, 1980; Clarke, in press). The river rises in the vicinity of the Landdroskop (1133 m AMSL), in the Hottentots Holland Mountain Range in the western Cape (Figure 1). The dominant vegetation comprises mountain fynbos, which typically consists of low, fire-adapted, sclerophyllous shrubland, with no canopy, and which has counterparts in the macchia of the Mediterranean Basin, the Californian chaparral, the mattoral of Chile and the heathlands of southeastern and southwestern Australia (King *et al.*, 1987). The climate is mediterranean, with a strongly seasonal rainfall; most rain falls in the austral winter (May–September).

The gradient of the Palmiet River is steep (Figure 2), falling 400 m in 4 km from the source, a further 300 m in the next 9 km and levelling off to fall *ca.* 300 m over the remaining 61 km to the sea (Clarke, in

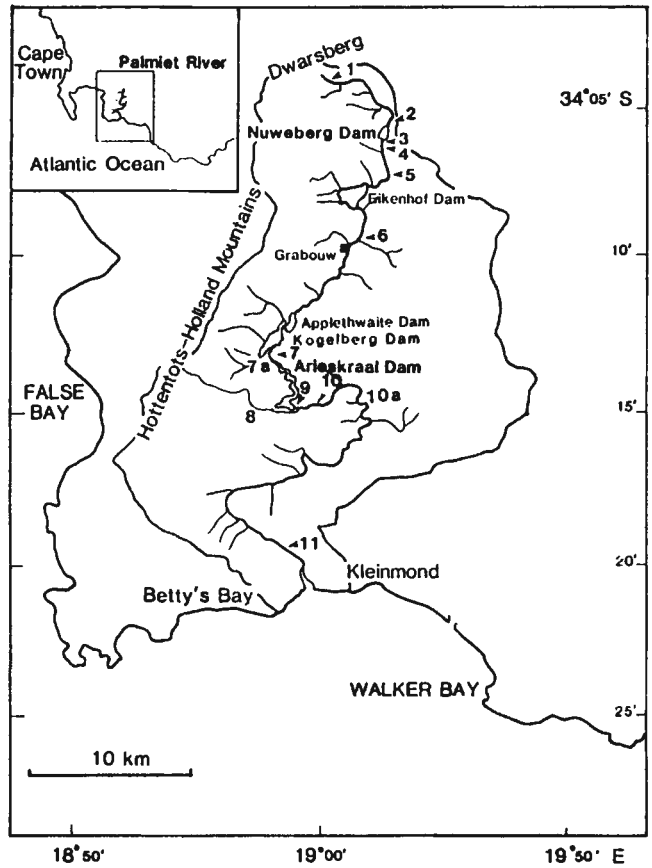

Figure 1. Map of the Palmiet River system showing the catchment outline, towns, major tributaries, sampling sites (1–11) and present impoundments. The inset shows the position of the catchment on the south coast of the southwestern Cape of South Africa

press). Three main zones can be discerned in the catchment area: pristine headwaters, agricultural area (predominantly fruit farming) and the Kogelberg State Forest (Figure 2). The geology of the upper and lower reaches comprises highly leached Table Mountain Sandstone (TMS), while the middle reaches flow over Shales of the Bokkeveld Series (Nel, 1980) (Figure 3). The river is impounded at five points within the first 40 km and then runs freely to the estuary which lies between Betty's Bay and Kleinmond (Figure 1; Table I). There are four irrigation storages, listed in order downstream: Nuweberg, Eikenhof, Applethwaite and Arieskraal, while between the last two is the lower dam of the Kogelberg Pumped Storage Scheme which came on stream in April 1987.

Eleven stations were established along the length of the river (Figure 1) and sampled monthly from February 1986 to August 1987. The physico-chemical conditions of the pristine headwaters, the inflow and releases from the uppermost dam (Nuweberg—P1; Figure 2), and a 2 to 3 km zone below it, as well as those of the lowermost structure on the system (Arieskraal Dam—P2; Figure 2), were primary targets for this study. In addition, station 11, just above the estuary (Figure 1), was selected to provide data on the potential impacts of a proposed dam, 'Hangklip', a large wall with deep release facilities, which may be constructed less than 3 km upstream from the estuary.

METHODS AND MATERIALS

Water for chemical analyses was collected, filtered through Watman GF/F filters, frozen on site on dry ice and processed in the laboratory after freezer storage at −18°C. Nitrites, nitrates, soluble reactive phosphate, and ammonium were analysed using a Technikon Auto-Analyser. Total alkalinity was

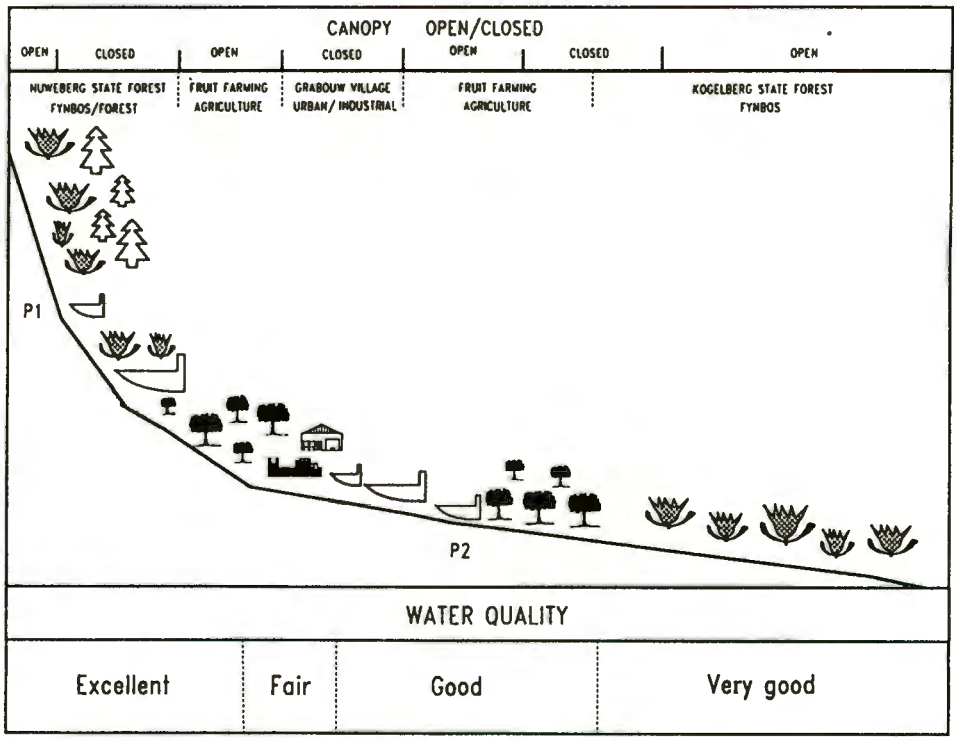

Figure 2. Schematic vertical profile of the Palmiet River showing catchment land uses, relative water quality, and the positions of the dams along the system. P1, Nuweberg Dam; P2, Arieskraal Dam

determined by the titrimetric method of Golterman *et al.* (1978), using 0·001 M HCl to a mixed indicator end-point. Chlorides were titrated against $HgCl_2$ to a diphenylcarbozone-bromphenol blue-mixed indicator end-point (Golterman *et al.*, 1978), while sulphates were analysed spectrophotometrically using a methylthymol blue and barium chloride colour reagent after the sample had been passed through an amberlite ion-exchange column (Technikon method).

Total suspended solids (TSS) were determined by difference after passing a known volume of water through a pre-combusted (450°C, 5 h), tared Watman GF/F filter, and drying at 60°C. The organic fraction was determined after further combustion. Total dissolved solids (TDS) were measured by mass difference after evaporation at 90°C of a known volume of filtered water (Watman GF/F 0·4–0·6 µm). Temperature was determined with a mercury thermometer, pH using a Lilliput Field pH meter and conductivity with a Crison Field Conductivity meter. Oxygen was calculated as percentage saturation after measurement with a YSI Dissolved Oxygen meter. Field observations of flow rate were made using an Ott C2 current meter and converted to volumes after measurement of stream profile at each station.

Unless otherwise stated, the data are presented as median values. The median was chosen as representative of base-flow trends within the system, minimizing the influences of extreme conditions of drought and flood, since the median is little affected by such extremes (*cf.* O'Keeffe *et al.*, submitted).

RESULTS

On average, flow volumes were low in the upper reaches (median flow rate, 0·18 $m^3 s^{-1}$), increasing downstream with a maximum above the estuary at site 11 (median, 3·1 $m^3 s^{-1}$) (Figure 4). Median flow volumes increased below Nuweberg Dam (site 3; Figure 4) and continued to increase to site 4, decreasing again at site 5. This was due to summer releases from the dam to supplement downstream irrigation requirements. During some winter months (August and September), from site 7 downstream, flow

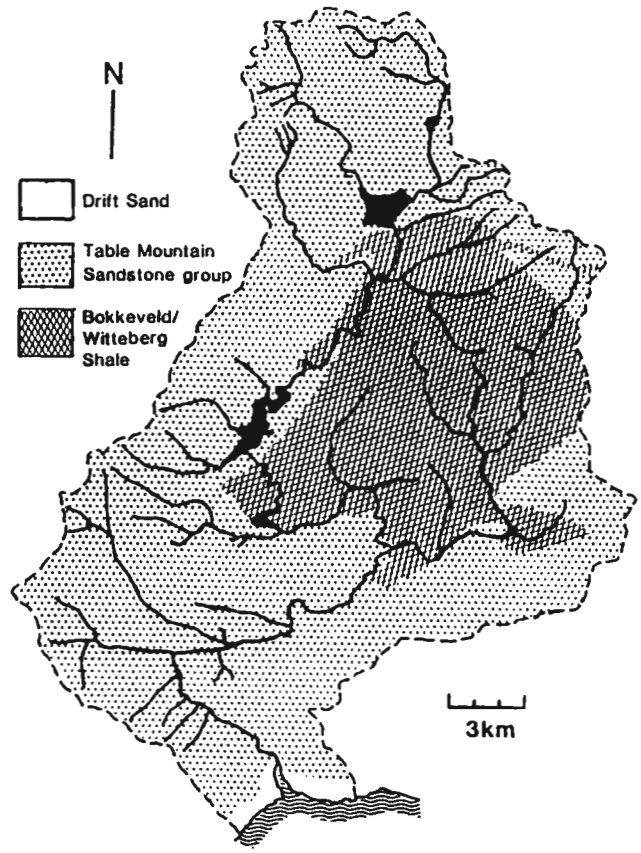

Figure 3. Geology of the Palmiet River catchment

Table I. Characteristics of the five dams along the length of the Palmiet River

	Nuweberg	Eikenhof	Applethwaite	Kogelberg	Arieskraal
Maximum capacity ($\times 10^6$ m^3)	0·38	22·1	?	19	5·9
Release depth	bottom	bottom	surface	middle	bottom
Distance (km) from source	6	12	21	25	31
Altitude (m)	510	340	250	210	200
Wall type/ height	earth fill	concrete	concrete	concrete/46 m	concrete
Use	holding	irrigation supply	irrigation supply	pumped storage	irrigation supply

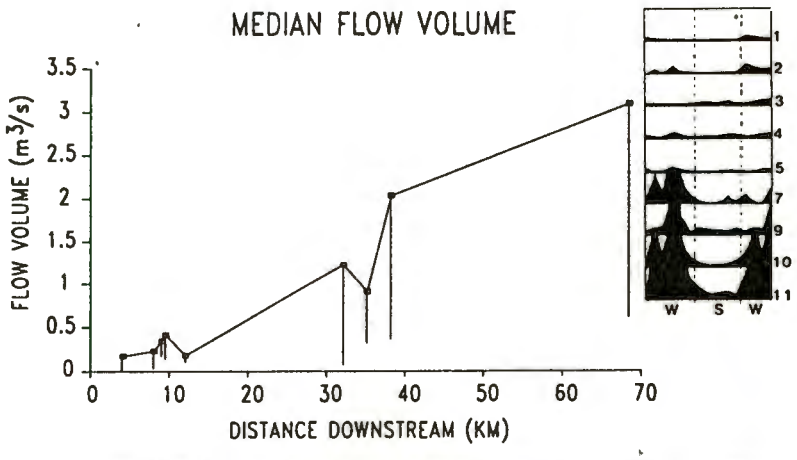

Figure 4. Median and minimum flow rates down the length of the Palmiet River for the eighteen month study period. Maxima are not shown due to their unmeasurability during the winter season. The inset shows seasonal trends by site downstream (1–11) over the study period

volume was not measurable due to very high discharges, while at the lowest site (11), flow volume was only measurable between October and March. Despite these problems, seasonality was pronounced; very high in the rainy season (winter), tailing off to minimum levels in late summer (February and March; Figure 4 inset).

An interesting anomaly in the discharge data of site 3 is illustrated in the inset in Figure 4. Here, there was more discharge in summer than in winter due to the fact that hypolimnetic releases are reduced at times when the spillway is full. Thus, during winter, epilimnetic releases which enter the river below site 3 replaced the hypolimnetic releases of other times of the year. Also of interest in Figure 4 is the fact that the first winter flows (April 1986) evident at site 7 were entirely absorbed by Arieskraal Dam; i.e. site 9 had no elevated discharges. In addition, the impact of the Kogelberg Dam is also clear; sites 10 and 11, for instance, showed flood flows in May 1987, while high flows at site 7 did not exist despite heavy rainfall at the time of sampling.

Median temperatures increased slightly (1·5°C) from the headwaters to the estuary (Figure 5a). Decreases below each dam were detectable, while the maximum temperatures occurred in the near stagnant waters at site 6 (Grabouw village). Temperatures were also apparently raised during the construction and closure of the Kogelberg Dam (site 7; Figure 5a). Excluding station 6 (stagnant and polluted site at Grabouw village), both Arieskraal and Nuweberg dams markedly depressed the annual temperature range (Figure 5b), with Arieskraal Dam showing a stronger influence (≈7°C) and Nuweberg a less pronounced effect (≈2°C).

The inset in Figure 5a illustrates seasonal trends in temperature at each station over 18 months. Obvious summer and winter trends were noted along the length of the river, while a definite decrease in summer, and a slight increase in winter temperatures occurred below both dams (refer, sites 2 to 3 and 7 to 9; Figure 5 inset). These differences were more pronounced at Arieskraal (site 9) than at Nuweberg (site 3). Figure 5 (inset) also shows a delay in both the vernal decrease and autumnal rise in temperature below Arieskraal.

Very low concentrations of $CaCO_3$ were recorded in the headwaters (sites 1–5; Figure 6a), while Grabouw showed an erratic distribution of fairly high $CaCO_3$ concentrations with slightly higher values in summer than in winter (inset, Figure 6a). The middle and lower reaches showed definite seasonal trends, with summer highs and winter lows (Figure 6a, inset). This seasonal distribution was shifted below Arieskraal, where instead of summer highs/winter lows, spring lows and autumn highs occurred (compare sites 7 and 9; inset, Figure 6a). Partial recovery became apparent at Site 10 (Figure 6a, inset), where a shift back towards the site 7 situation occurred. Relatively low concentrations, and poor summer–winter variation was evident above the estuary (site 11; inset, Figure 6a).

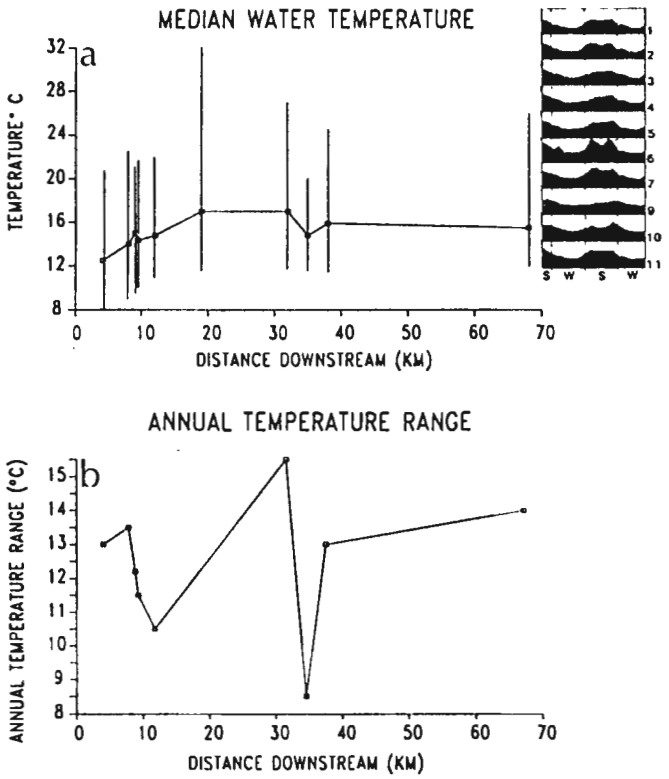

Figure 5. Median, minimum and maximum spot temperatures (5a) and annual temperature range (5b) down the length of the Palmiet River for the eighteen month study period. The inset for 5a shows seasonal trends in spot temperature by site downstream (1–11) over the study period

The pH generally increased from headwaters to mouth (Figure 6b), with extremely acid waters near the source (sites 1–5; medians 4·0–4·5). Highest values were recorded below the Kogelberg Dam construction site (site 7; median 6·5, maximum 8·6). Median pH increased below Nuweberg but decreased below Arieskraal (Figure 6b).

The river was well oxygenated down its length (Figure 6c), with a slight increase below each dam and supersaturation often occurring during periods of heavy rain and high flows. The lowest levels (44 per cent saturation) were recorded at Grabouw.

Suspended solids were lowest in the headwaters (median 0·52 mg l^{-1}), with a very slight overall increase towards the estuary (median 2·44 mg l^{-1}; Figure 6d). Increases were noted below each dam, with maxima at sites 3 and 9 (respectively, 4·8 and 6·0 mg l^{-1}), followed by a gradual decrease towards sites 5 and 11 (respectively, 2·9 and 2·44 mg l^{-1}). Concentrations peaked at all sites after the first heavy rains of winter, falling to lowest levels around spring and early summer. Maximum values were recorded at the polluted site of Grabouw (median 11·03, maximum 102·4 mg l^{-1}).

Ionic concentrations increased from source to mouth but were fairly low all year round (Figures 6e, f), highest values at all sites being recorded at the beginning of winter. In general, both conductivity (Figure 6e) and TDS (Figure 6f) showed only extremely small decreases below each dam. However, both parameters showed an expected increase along the river from source to mouth as well as maxima at the polluted Grabouw site (station 6; Figures 6e, f).

Chloride (Figure 7a) and sulphate (Figure 7b) concentrations were generally low at the source (respectively 7·8 and 0·78 mg l^{-1}), increasing towards the mouth. Median chloride levels marginally decreased below each dam, whereas sulphate levels increased below Nuweberg (by 24 per cent) and decreased below Arieskraal (14 per cent).

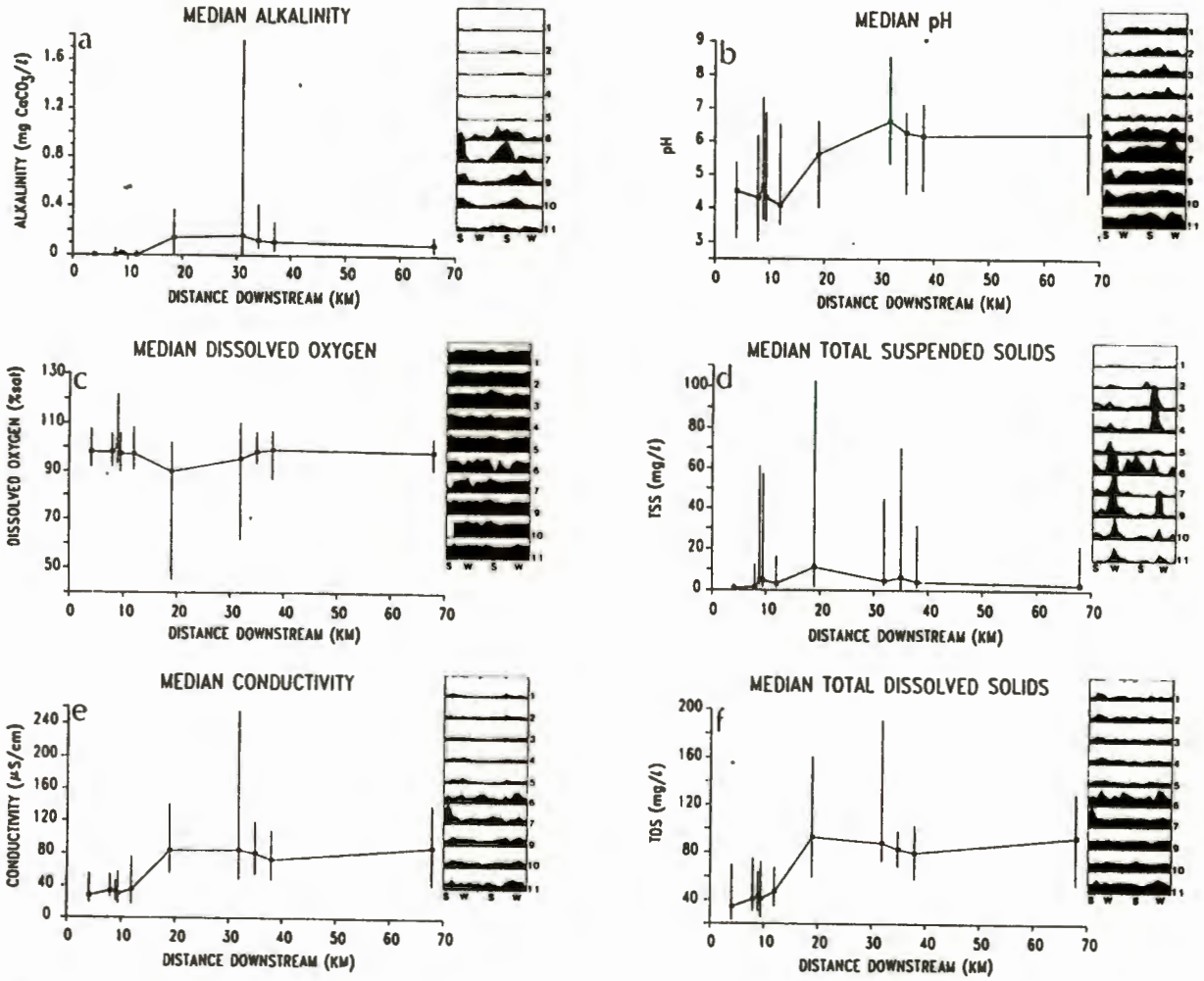

Figure 6. Median, minimum and maximum values of: (a) alkalinity; (b) pH; (c) dissolved oxygen; (d) total suspended solids; (e) conductivity, and (f) total dissolved solids, down the length of the Palmiet River for the eighteen month study period. The insets show seasonal trends for each parameter by site downstream (1–11) over the study period. See text for explanation

Low nutrient concentrations were recorded in the headwaters with levels increasing towards the middle reaches and subsequently decreasing towards the estuary (Figures 7c–f). In the case of NO_2^-, NO_3^{2-}, and PO_4^{3-}, median values were higher at the estuary (respectively, 10·5, 609·6, and 33·2 $\mu g l^{-1}$) than at source (respectively, 5·98, 19·84, and 25·64 $\mu g l^{-1}$), while for NH_4^+ the concentrations were similar (source, 51·26 and site 11, 46·48 $\mu g l^{-1}$). Annual differences for nitrites and nitrates were evident, with spring highs and autumn lows in the upper reaches for nitrites and in the lower reaches for nitrates. On the other hand, there were no clear seasonal variations for phosphate and ammonium. Median levels of NO_2^- (Figure 7c), NO_3^{2-} (Figure 7d) and NH_4^+ (Figure 7e) increased below each dam, but PO_4^{3-} (Figure 7f) levels marginally decreased below Nuweberg and increased below Arieskraal Dam.

DISCUSSION

Ward (1976b), Brooker and Hemsworth (1978), King and Tyler (1982), Armitage (1984), Cowx *et al.* (1987), and Wright and Berrie (1987) have discussed aspects of the impacts of flow regime alterations by dams on receiving reaches. Ward (1976b) lists four basic flow pattern alterations in the context of impacts

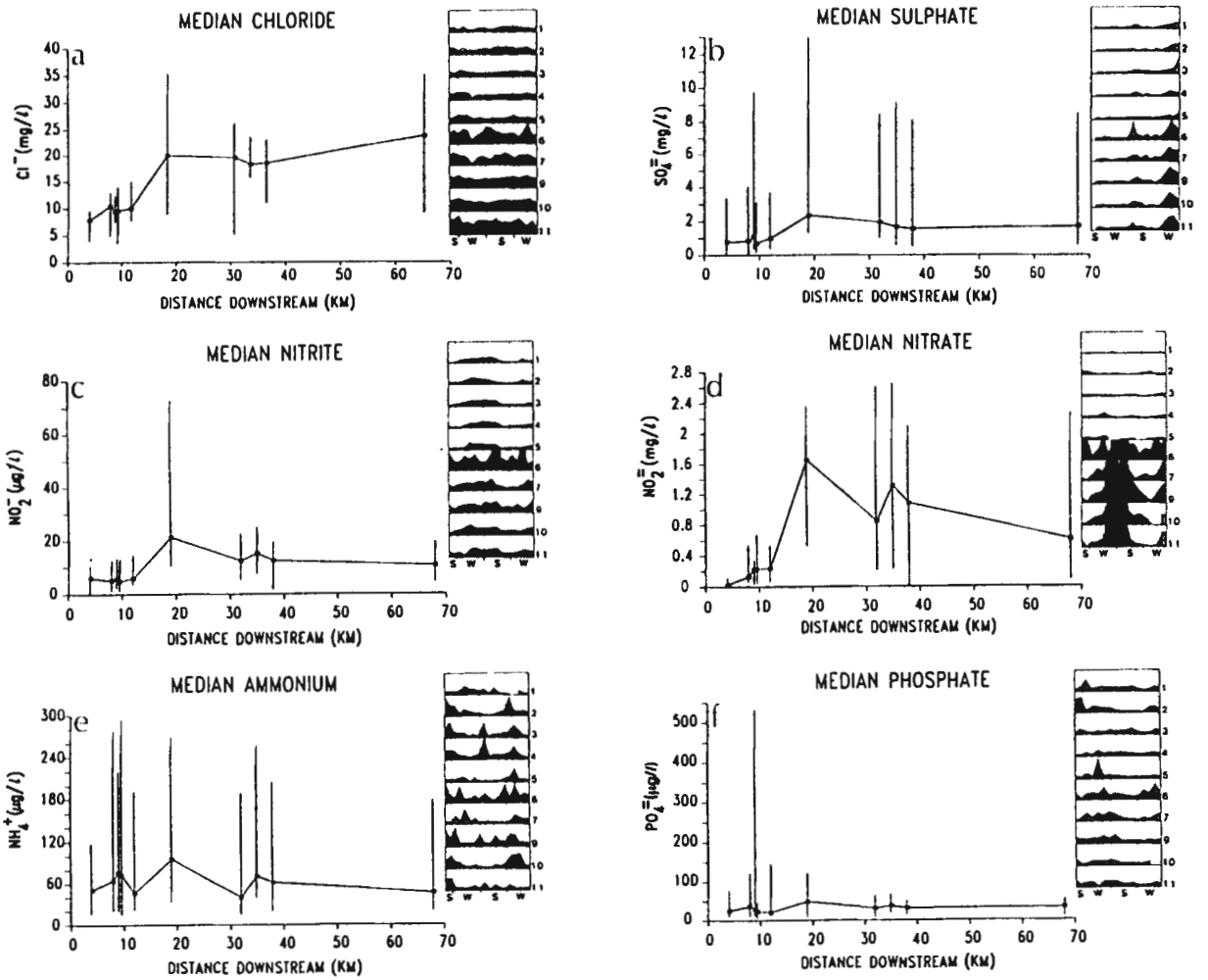

Figure 7. Median, minimum and maximum values of available nutrients: (a) chloride; (b) sulphate; (c) nitrite; (d) nitrate; (e) ammonium, and (f) soluble reactive phosphate, down the length of the Palmiet River for the eighteen month study period. The insets show seasonal trends for each parameter by site downstream (1–11) over the study period. See text for explanation

upon the benthic invertebrates of streams: seasonal flow constancy; short-term fluctuations; reduced flows, and increased flows. In addition to these, our study has shown that impoundments may also *reverse* the seasonality of flow volume. Interestingly, Chutter (1973) noted that reversal of the seasonality of flow volume, i.e. greater volumes in the dry season than in the wet season, was likely for receiving reaches below power-production impoundments in summer rainfall areas, such as occur on the South African Highveld. Here, winter power demands and summer storage cause total reversal of natural flow patterns.

In the case of the Palmiet, situated in a *winter rainfall* area, both flow constancy and flow reversal occur, but below different dams. For instance, our data for Nuweberg Dam (an irrigation supply structure) show reversal; increased summer and decreased winter flows (inset, Figure 4; sites 2 and 3). On the other hand, Arieskraal Dam produces flow constancy (inset, Figure 4; sites 7 and 9). These differences are not due to the relative positions of the two dams on the river. Nuweberg Dam in the upper reaches is managed such that it supplies a lower dam (Eikenhof; Figure 1) with irrigation water on demand—greater volumes are released in summer, when flows should be low. Arieskraal, on the other hand, although an irrigation storage, has a much larger volume and can sustain a more constant flow to the lower river throughout the year. The implications of such alterations for invertebrates in terms of

reduction in habitat diversity as well as for food supply must be considerable and studies are currently underway to determine community structure and diversity.

The seasonal flow reversal caused by Nuweberg Dam 'recovers' within 3 km of the dam (by site 5; see inset, Figure 4). This rapid recovery is effected by epilimnetic spilling in winter, which enters the river below site 3, and irrigation abstraction in summer above site 5. In the case of the flow constancy caused by Arieskraal Dam, the normal seasonal flow regime (but with slightly elevated summer flows) is re-established by station 10, some 3 km below the wall, owing to epilimnetic discharge during high flows, and contributions from a major tributary, the Klein Palmiet, which enters the river between sites 9 and 10.

Wide seasonal variations in temperature favour high biotic diversity (Ward and Stanford, 1979b). River regulation tends to decrease seasonal variation in temperature, with concomitant effects upon the biota (e.g. Ward, 1976a; Krenkel *et al.*, 1979; Ward and Stanford, 1979b; King and Tyler, 1982; Armitage, 1984; Cowx *et al.*, 1987). General alterations include diel and seasonal constancy, summer cooling and winter warming (e.g. Ward 1976a, 1985; Webb and Walling, 1988). Penaz *et al.* (1968) and Gore (1977) have reported a reduction in faunal diversity with decreases in annual temperature range. Even without large changes in the mean annual temperature, it is important to note that large modifications to the total thermal pattern may occur with considerable impacts upon faunal components; pronounced thermal alterations may have significant impacts on seasonal timing of major biotic processes such as insect emergence and growth rates (e.g. Ward, 1982, 1985; Raddum, 1985).

The effects of impoundment on the downstream water temperatures of the Palmiet are clearly demonstrated below both Nuweberg and Arieskraal dams, with a large decrease in summer and a slight rise in winter (Figure 5a). There is also a reduction in seasonal variation (Figure 5a, inset). In other words, summer cooling, winter warming and seasonal constancy are demonstrated in the system. Although we have not yet verified a decrease in faunal diversity for the Palmiet, this will form the basis of later analyses.

The decrease in annual temperature range below Nuweberg Dam (site 3; Figure 5b), is due to hypolimnetic discharge. It was maintained and slightly accentuated for 5 km downstream due to shading by low canopy shrubs. In other words, no 'recovery' was detected in the flowing reaches of the river above the next impoundment on the system (Eikenhof; Figure 1). The annual temperature range then increased to a maximum above Arieskraal, dropped very sharply below the dam, and then increased gradually towards the estuary, but never attained the range recorded for site 7 above Arieskraal Dam. Recovery of thermal regimes altered by stream regulation can take tens or even hundreds of kilometres, depending on the thermic slope (the difference between air and water temperatures) and discharge (Ward 1982). In the case of the Palmiet, a 'recovery distance' greater than 30 km below Arieskraal Dam appears necessary under the prevailing environmental and physical conditions, but the river is too short to accommodate this.

An examination of the Serial Discontinuity Concept (SDC) of Ward and Stanford (1983) shows a major difference between our data and their predicted trends for annual temperature range. For instance, the SDC predicts little impact by upper-reach dams, but major impacts by mid- and low-reach structures (see Figure 1f, p. 32 in Ward and Stanford, 1983). In the precipitous Palmiet, a distinct impact is caused by the upper-reach dam, with no recovery before the next impoundment (see above) (Figure 5b), while for the mid-reach dam, a major thermal impact is obvious due to hypolimnetic discharge (Figure 5b).

The Palmiet is acid in its upper reaches, due both to poorly buffered and porous Table Mountain Sandstone (Nel, 1980), and to humic acids from partly decomposed fynbos. Krenkel *et al.* (1979) have observed that pH tends to be more frequently lower in the hypolimnion of reservoirs, compared to the epilimnion. Judging from the impact of Nuweberg and Arieskraal dams on receiving reaches of the Palmiet, this appears to be the case for the latter, but not for the former, the extremely acid upper-reach waters of the system and the relatively shallow nature of Nuweberg possibly accounting for this difference.

Alkalinity and pH in the Palmiet are higher in summer (Figures 6a, b, insets); the more acid waters in winter resulting from higher runoff and groundwater flushing. As in the case of seasonal temperature trends (inset, Figure 5a), impoundment of the Palmiet alters the seasonal trends in alkalinity. Normal

summer-high and winter-low conditions are shifted below Arieskraal (spring low, autumn high), with a subsequent partial recovery at site 10, and a full recovery at site 11 (inset, Figure 6a). Such impacts may be a function of retention time within the reservoir as well as its constant release pattern. On the other hand, Nuweberg does not cause similar changes (Figure 6a) and the differences between the two dams may be due to the fact that the upper reaches of the river are extremely acid, and hence, are a function of their relative positions along the system.

The high values for alkalinity recorded at site 7 are due to the release of cement/lime compounds during the construction of both the Kogelberg Dam and a gauging weir immediately downstream from the dam. In this context, site 7 was the only site where gastropod Mollusca have been found (unpublished data).

Grégoire and Champeau (1984) maintain that the hypolimnion of storage reservoirs contains high dissolved oxygen concentrations and that, therefore, this results in the '...satisfactory oxygenation of water downstream from dams.' Ward (1982) and Armitage (1984), on the other hand, state that deoxygenation is often associated with deep-release reservoirs. We would hold to the latter view, observing, as Ward (1982) and Armitage (1984) point out, that recovery of oxygen-depleted water is usually very rapid due to turbulent discharge. In the Palmiet River, adequate oxygenation occurred throughout its length (Figure 6c), with supersaturated water being released, at times, from Nuweberg Dam (maximum, 123 per cent).

Impoundments usually act to settle out fine silt particles (Hudson *et al.*, 1949; Buttling and Shaw, 1973), releasing much clearer water immediately below the outfall, which subsequently becomes highly erosive (Pemberton, 1974; Simons, 1979; Krenkel *et al.*, 1979; Guy, 1981; Gilvear, 1988). In the Palmiet (Figure 6d), there is no evidence of 'clear' releases immediately below Nuweberg and Arieskraal in relation to the inflows to these dams. Thus, bank erosion and channel-bed flushing, such as observed by Gilvear and Petts (1985) in Afblithefield Reservoir, do not occur in the Palmiet River. Below Nuweberg Dam, the levels of suspended solids partially recovered (decreased) within 3 km of the wall, while below Arieskraal, recovery occurred within 3 km. Given the low TSS of our system it is unlikely that major impacts upon the biota, of the type recorded by Gray and Ward (1982), Culp *et al.* (1986) and Perry and Sheldon (1986), will be evident.

Turning to ionic concentrations, Ward (1982) has observed that both the inflowing and outflowing waters of reservoirs may sometimes closely resemble each other, should coherent density currents occur in the system. However, this frequently is not the case and considerable differences in the quality of influent and effluent waters may occur depending upon reservoir morphometry and retention time. In the Palmiet, the retention times of the study reservoirs are unknown, but we have observed only very slight changes (decreases) in both conductivity and TDS (respectively, Figures 6e, f) below both dams.

In this context, the only southern African works which deal with ionic changes as the result of river regulation come from Toerien and Walmsley (1978) and O'Keeffe and De Moor (1988). Toerien and Walmsley (1978) showed that the mineral content of the waters flowing out of the Hartbeespoort Dam were not subject to the same seasonal variations as occurred in the Crocodile River above the dam because of both biological and chemical conversions within the reservoir. O'Keeffe and De Moor (1988) examined changes in the Great Fish River brought about by an inter-basin transfer of water from the Orange River. Basing their observations on pre-transfer data published by Hall and Du Plessis (1984), O'Keeffe and De Moor (1988) noted that the 500–800 fold increase in flow and change from a seasonal to perennial system had also led to dilution of salt levels in the recipient system (particularly Na^+, Mg^{2+}, Cl^- and SO_4^{2-}—but not for Ca^{2+} or Total Alkalinities). Obviously, considerable effort is still required before differences in such changes for the various chemical species can be elucidated.

In the international context, Shields and Sanders (1986) showed that conductivities in the regulated Yellow Creek system (Mississippi) did not vary seasonally. In our study there was also no seasonal variation, with only minor peaks in ionic concentrations at the start of the rainy season (April; Figure 6e), as a result of leaching, runoff, and overall flushing of the system.

As far as nutrients are concerned, it is well known that reservoirs may act as nutrient sinks, and the quality of reservoir releases will greatly depend upon both their timing and their depth characteristics (e.g. Ward, 1982; Armitage, 1984). For example, large nitrogen and orthophosphorus loads were measured by Rada and Wright (1979) from the hypolimnion below 25 m depth in Canyon Ferry

Reservoir, Montana. In the Palmiet, nitrite, nitrate, and ammonium all increased below each dam due to similar hypolimnetic discharges (respectively, Figures 7c–e). These increases were temporary and returned to upstream levels within 1 km below Nuweberg and 3 km below Arieskraal. Such increases in nutrient concentrations below impoundments may have far reaching effects for the biota immediately below the wall, with subsequent repercussions on ecological processes further downstream (e.g. Petts, 1980).

Both nitrite and nitrate in the Palmiet (Figures 7c, d) showed very obvious temporal and spatial variations, with lowest values recorded in autumn and in the headwaters, and highest values recorded in spring and in the middle and lower reaches; probably due to runoff, leaching and to agricultural

Table II. Summary of the effects of the upper (Nuweberg, P1) and lower reach (Arieskraal, P2) dams on the Palmiet River. 'Recovery distances' (km) are listed below each effect for each attribute of the system. Where relevant, seasonal shifts and their recoveries are also noted

	D A M	
	P1	P2
Feature		
size	small	medium
reach	upper	middle
release	bottom	bottom
nutrient status	low	low
Variable	*effect: medians/seasonality* recovery distance (km)	
Flow	*increase/reversal* none/ 3	*decrease/constancy* 3/ 3
Temperature	*increase/displace* partial/ 3	*decrease/displace* partial/ 3
Temperature range	*decrease* none	*decrease* partial
pH	*increase* 0·5	*decrease* none
Alkalinity	*increase* 3	*decrease/displace* none/30
TSS	*increase* partial	*increase* 3
Conductivity/TDS	*little effect*	*little effect*
NO_3	*increase* none	*increase* 3
NO_2	*increase* 0·5	*increase* 3
NH_4	*increase* 3	*increase* 30
SRP	*decrease* none	*increase* 3

influences. Soltero *et al.* (1973) and Ward (1982) have noted that the temporal patterns displayed by a variety of chemical species may be shifted in ways similar to those we have observed for flow and temperature in the Palmiet. However, our chemical data show no similar temporal shifts. Seasonal variations occur normally throughout the system (Figures 7c, d). A study of the retention times of both Nuweberg and Arieskraal dams would possibly throw some light onto these issues.

CONCLUSIONS

The two major changes which have occurred in the Palmiet River as a result of impoundment involve flow and temperature. The system which lies in a winter rainfall region, shows both flow constancy and reversal, but below different dams: the upper dam shows reversal (increased summer and decreased winter flows); the lower, flow constancy. These differences are, however, more likely to be due to their relative size and use, rather than to their relative positions on the river. This finding contradicts the thesis of Ward and Stanford (1983). Water temperature changes are also profound, with pronounced summer cooling and winter warming, together with a reduction in seasonal temperature variation. These changes and their recovery distances are summarized in Table II, together with those for the other physico-chemical attributes of the system examined during this study.

Although many effects appear to recover within relatively short distances below each dam, it must be noted that the Palmiet is itself a *very short*, precipitous river only 74 km long. Even recovery distances of 3 km, in terms of overall length of the system, represent considerable perturbations to the system as a whole. For attributes such as temperature throughout the system, only partial recovery takes place, while for PO_4^{3-} and NO_3^- below Nuweberg and for pH, alkalinity and NH_4^+ below Arieskraal, recoveries are either non-existent or prolonged. It is clear that as far as management of the system is concerned, care is needed and serious impacts such as seasonal reversals of temperature, alkalinity, and flow require urgent attention. Certainly, the case for better design and more careful operation procedures for dams in the region is obvious.

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ERRATA

Page 61 line 17 Watman = Whatman

Page 2 line 7 Watman = Whatman

Page 64 line 26 the sentence should read "Very low concentrations of total alkalinity, expressed as $CaCO_3$, were recorded ...."

Explanatory note:

In response to the query from an external examiner that, although 11 sites were sampled, there are only 10 sites on the graphs in Figures 4, 5, 6, and 7, it should be explained that site 8 was not included on the graphs as it did not occur on the main stream, but on a tributary, the Klein Palmiet. Since water is abstracted from the Klein Palmiet into the lowermost impoundment, Arieskraal, and the tributary enters the river between sites 9 and 10, *ca* 2 km downstream of Arieskraal, site 8 was monitored in order to determine whether or not it could have an influence on the water within the impoundment and/or on the river downstream of Arieskraal.

SUSPENDED PARTICULATE MATTER TRANSPORT IN A REGULATED CAPE MOUNTAIN STREAM.

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SUSPENDED PARTICULATE MATTER TRANSPORT IN A REGULATED CAPE MOUNTAIN STREAM.

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ABSTRACT

The proliferation of dams has necessitated a fuller understanding of the effects of stream regulation but has also provided a setting for testing and developing basic theories of stream ecology. This study quantifies some of the changes in the transport of suspended particulate matter downstream of two impoundments, with specific reference to two important concepts in stream ecology, the River Continuum Concept (RCC) and the Serial Discontinuity Concept (SDC). Suspended particulate matter was collected monthly from April 1986 to April 1988. Quantities of total suspended solids, comprising predominantly ultra fine particulate matter, increased from source to mouth with uncharacteristic increases below both impoundments. The larger size fractions (very fine, fine and coarse particulate organic matter) showed highly variable downstream changes and varying responses to regulation, as did the CPOM:FPOM ratio. There was a noticeable increase in particulate loads during autumn/winter although the percentage of organics was highest in summer/autumn. There was a strong positive correlation between annual discharge and annual suspended particulate loads. Cluster analysis of all the variables with respect to site identified the sites immediately downstream of the impoundments as distinctly different from other sites. Distances within which recovery occurred were variable and the SDC was found to apply only to some sections of the river. It is concluded that the use of theories to predict ecosystem responses to perturbation, in order to manage river ecosystems, must be approached with great caution.

INTRODUCTION

Unidirectional transport is an important element in conceptualising streams as longitudinally linked systems (Vannote *et al.*, 1980; Minshall *et al.*, 1985; Cuffney and Wallace, 1988) or as net importers or exporters of energy, nutrients or organic matter (Cummins 1974). Transport of suspended material in lotic systems is a complex phenomenon dependent upon both the systems' hydrologic characteristics and the hydrodynamic character of the seston (Kazmierczak *et al.*, 1987). In altering the natural flow of a stream several environmental issues should be considered in order to manage discharges so as to maintain river ecosystem functioning. These include the need for flushing flows (Reiser *et al.*, 1985), flow

requirements for aquatic organisms (e.g. Gore, 1985) and the effect of increased sediment loads on the stream ecosystem (DeBrey and Lockwood, 1990).

The dominant energy source of small woodland streams is allochthonous (Petersen and Cummins, 1974). Much work has been directed at quantifying terrestrial inputs to streams (e.g. Fisher and Likens, 1973; Winterbourn, 1976; Conners and Naiman, 1984; King *et al.*, 1987; Richardson and Neill, 1991) and on the instream transport of particulate organic matter (e.g. Bormann *et al.*, 1969; Dance *et al.*, 1979; Naiman and Sedell, 1979). Organic material drifting downstream represents a one-way coupling of energy from upstream areas to downstream reaches (Webster, 1975) and this is important for 'nutrient spiralling', the cyclical nature of nutrient availability in lotic ecosystems (Webster, 1975; Wallace *et al.*, 1977). Food quality is important in determining the degree of spiralling and the effectiveness of the system in retaining and processing organic material (Naiman and Sedell, 1979).

The influence of river regulation on the sediment-carrying capacity of streams (Simons, 1979; Webster *et al.*, 1979; Petts and Thoms, 1986; Petts, 1988), as well as the effect of sedimentation on channel structure (Gilvear and Petts, 1985; Petts and Greenwood, 1985; Gilvear, 1988) and benthic invertebrate communities (Chutter, 1969; DeBrey and Lockwood, 1990) have also been well researched. Channel response to an imposed flow regime is known to involve the interaction of changes to a number of morphological variables (e.g. Hey, 1979; Petts and Thoms, 1986). During the 1950s field evidence of an erosional response to loss of sediment load below dams showed not only channel-bed degradation but also changes of substratum particle size (Stanley, 1951) and related changes of roughness and flow velocity (Einstein and Chien, 1958), i.e channel armouring. The increased sedimentation rates behind navigation dams (Bhowmik and Adams, 1986, Chen and Simons, 1986) was found to cause a steady loss of river width and volume resulting in increased flood intensities in the Mississippi River (Grubaugh and Anderson, 1989).

In southern Africa the sedimentation of reservoirs is resulting in a reduction in the water available for irrigation and is thus becoming a major threat to much needed agricultural expansion (Kabell, 1984; Magadza, 1984; Walling, 1984). A study on the Buffalo River in the eastern Cape, South Africa (Palmer and O'Keeffe, 1990), found that the effects of

impoundment depended largely on the type of release and the quality of the inflowing water: surface-releasing reservoirs in the clean, upper reaches of the river had least effect on transported material.

South African impoundments have also encountered major problems due to excessive enrichment with frequent blooms of microscopic algae. However, Palmer and O'Keeffe (1990) concluded that most of the downstream changes in transported organic matter in the Buffalo River were due to inflows of agricultural and urban effluent. These disturbances to the river cause greater perturbations than do the impoundments (Palmer and O'Keeffe, 1990).

Few long-term studies have been undertaken on entire river systems, aimed at assessing the effects of regulation on different aspects and implications of particulate matter transport in streams, and/or at assessing the validity of certain stream ecology hypotheses. This study attempts to quantify the downstream changes in the transport of suspended particulate matter in relation to impoundment, and to discuss these changes with specific reference to the River Continuum Concept (RCC: Vannote *et al.*, 1980) and the Serial Discontinuity Concept (SDC: Ward and Stanford, 1983). With respect to transported particulate matter the RCC and SDC address two factors: CPOM:FPOM ratio and zooplankton abundance. The RCC views rivers as longitudinal systems whose biotas are predictably structured by resource gradients and the SDC interprets impoundment as an interruption in those longitudinal gradients. The SDC hypothesises that within a certain distance downstream of an impoundment a specific variable will return to its predicted position in the river continuum. This distance is termed the "discontinuity distance". Since no pre-impoundment data were available for the Palmiet River the term 'recovery distance' has been invoked and is defined as *that length of stream which is required for any parameter to return to values close to those measured at the inflow to the impoundment, or to achieve a new dynamic equilibrium* (Byren and Davies, 1989; O'Keeffe *et al.*, 1990).

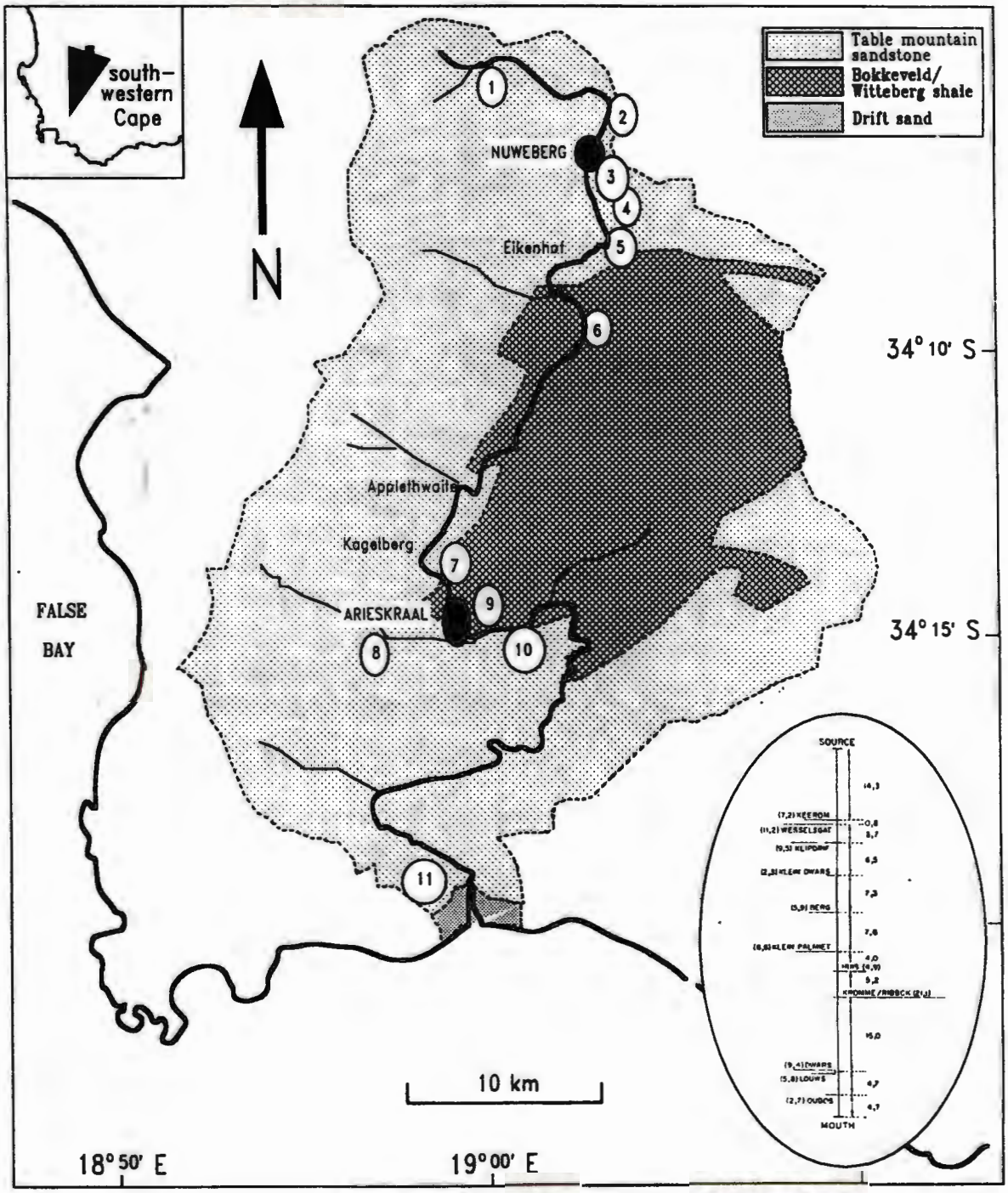


Figure 1: Map showing the Palmiet River Catchment, the underlying geology, the position of the two impoundments studied, the position of the sampling sites and the location of the other impoundments on the system. The inset shows the major tributaries, their lengths (in parentheses) and the distances between each one at their point of entry to the Palmiet River.

STUDY AREA

The Palmiet River, south-western Cape (Figure 1: detailed in Byren & Davies, 1989) is a 74 km long, cool, acid, blackwater, mountain stream, draining a catchment of approximately 500 km^2 (Nel, 1980; Clarke, 1989) with a mean annual runoff (MAR) of 228 x 10^6 m^3 (Mr Nel, Dept Water Affairs, pers comm.). The river is situated in a mediterranean climatic region with a strongly seasonal winter rainfall. The river ranges between 3 and 45 m in width and flow rate varies from 0.02 to 1.0 m^3 s^{-1} in summer and from 0.32 to >4.0 m^3 s^{-1} in winter. The river substratum consists mainly of pebbles, stones and boulders throughout except for two short stretches, each about 2 km long, of sandy substratum, one in the upper-middle and one in the lower-middle reaches.

The underlying geology of the catchment is predominantly sandstones of the Table Mountain Series (TMS) in the upper and lower reaches, and Bokkeveld shale in the middle reaches (Clarke, 1989). The sandstones are vegetated mainly by Fynbos, the indigenous shrubland of the southern cape, consisting of hard, sclerophyllous, fire-adapted species, providing very low canopy cover and no cover over some rivers e.g. the upper reaches of the Palmiet River. The shales are extensively utilised for agriculture, predominantly fruit farming, and the riparian vegetation in this reach consists mainly of alien trees (*Acacia* spp), reeds and emergent aquatic macrophytes, especially the indigenous *Prionium serratum* (L.f.) Drege ex E. Meyer (the palmiet "reed"). The river is impounded five times within the first 40 km. Two of the five impoundments were chosen for this study, the upper-most, Nuweberg, and the lower-most, Arieskraal, as the downstream reaches below each impoundment were of sufficient length (7 km and 37 km, respectively), and undisturbed (except for the dams), so that recovery distances (*sensu* O'Keeffe et al., 1990) could be investigated. Eleven sites were chosen down the length of the river: one in the pristine upper reaches (PR1), one above (PR2) and 3 sites below Nuweberg (PR3-5), and one above (PR7) and 3 sites below Arieskraal (PR9-11). Site PR7, although immediately above Arieskraal, is also 0.5 km below the second-last reservoir on the system, Kogelberg. This is the lower reservoir of a pumped-storage scheme and was completed in April 1987, half-way through the study. Immediately below Kogelberg is a settling pond and immediately above PR7 is a gauging weir. An additional site (PR8) was also selected on the Klein

Palmiet, a tributary from which water is directly abstracted into Arieskraal. A site in the village of Grabouw (PR6) was only sampled for physico-chemical variables (see Byren and Davies, 1989). The two sandy stretches are situated mid-way between site PR5 and PR7 in the upper middle-reaches and approximately 2 km below site PR10 in the lower middle-reaches.

Table 1: Study sites and a brief description of their characteristics

SITE	DESCRIPTION (distance from source (km); position with respect to dams; bed type)	WIDTH (range) (m)	DEPTH (range) (cm)	FLOW ($m^3 s^{-1}$) median	minimum
PR1	4 km; pristine headwaters; boulders	1-8	7-46	0.1672	0.0045
PR2	8 km; above Nuweberg; gravel	2-24	28-92	0.2236	0.0282
PR3	9 km; below Nuweberg; rocky	2.5-3.5	12-72	0.3417	0.1646
PR4	9.5 km; below Nuweberg; concrete causeway	8-9	15-78	0.4107	0.1370
PR5	12 km; below Nuweberg; weir, rocky	2-9	30-58	0.1738	0.0861
PR6	in the village of Grabouw	not sampled for suspended solids			
PR7	32 km; above Arieskraal, below Kogelberg; weir, rock & gravel	3-7	30-53	1.2254	0.0533
PR8	34 km; tributary, Klein Palmiet, water abstracted to Arieskraal; stony	23-45	36-69	1.8338	0.3171
PR9	35 km; below Arieskraal;boulders	14-16	35-50	0.9085	0.3257
PR10	38 km; below Arieskraal; boulders	8-12	45-70	2.0317	0.3545
PR11	68 km; ≈3 km above estuary; boulders	11-20	105-143	3.0783	0.5929

METHODS

Samples of suspended particulate matter were collected monthly from April 1986 to April 1988 except in June and July 1986, when most samples were unobtainable due to strong spate conditions. One sample was taken at each site on each sampling occasion. Current velocity was measured at each site using a Zeis Ott C2 current meter and accurate stream profiles were taken in order to calculate discharge. Velocities could not be measured at certain sites in the lower reaches during mid-winter as spate conditions prevented access to the river. The samples for the coarser particulate fractions were taken by using an 80μm mesh-net with a mouth opening of 0.048 m^2 and a tail of 0.5 m, submerged just below the

surface, for between 5 and 10 minutes, depending on the rate of clogging (Douie, 1988). An Ott C2 current meter was placed at the mouth of the net to record current velocity through the net to allow calculation of the total volume of water passing through the net using the equation:

vol. (m^3) = net mouth area (m^2) x flow rate (m s^{-1}) x time (s) over which sample taken.

The ultra fine particulate matter (UPM) was obtained by pre-filtering water through an 80μm mesh sieve and then a known volume through pre-weighed, pre-combusted Whatman GF/F filters thus collecting the particulate matter between 0.7 μm and 80 μm in size. The samples from the drift net (>80 μm) were preserved in 5% formalin and returned to the laboratory for processing. In the laboratory the samples were split into three size fractions (80-250 μm: very fine particulate matter or VPM; 250-950 μm: fine particulate matter or FPM; >950 μm: coarse particulate matter or CPM), and stored in 1% phenoxitol. The animals were removed for an analysis of invertebrate drift (Paper III, this thesis). The remaining material was dried, weighed, combusted at 450 °C for two hours and re-weighed to determine the organic (POM) and inorganic (PIM) fractions.

Median values for each variable for each site were calculated and are illustrated graphically to indicate broad changes down the length of the river as well as the general effect of the two impoundments. The median was chosen as it is assumed to be a good indication of base-flow trends and is least affected by extreme environmental conditions (Byren and Davies, 1989; O'Keeffe et al., 1990; Palmer and O'Keeffe, 1990). It is assumed that by using median values, the effects of e.g. droughts and floods do not mask the general effects of the impoundments. Data on suspended particulate matter were analysed as medians by size class (coarse, CPM, fine, FPM, very fine VPM and ultra fine UPM), in three different ways: total particulate matter (PM), organic (POM) and inorganic (PIM) fractions, and percentage organic fraction. Median quantities of TSS and median percent organics for the TSS were calculated from the original totals of all size classes combined, and not from the medians of the individual size classes. Percent distribution of the different size classes, annual discharge and the particulate loads at each site as well as the relationship between discharge and quantities of suspended solids were calculated for each site and for each size

class. Variables are said to increase or decrease below impoundments with respect to the "above-impoundment" values.

CPOM:FPOM ratios were calculated in order to compare the present results with those predicted by the proposers of the RCC and the SDC. Since the size-classes used by Vannote *et al.* (1980) were CPOM > 1 mm and FPOM 50 μm to 1 mm, FPOM and VPOM in the present study were combined.

Data were grouped by site and season (winter = June - August; spring = September - November; summer = December - February; autumn = March - May), and were initially tested for normality using STATGRAPHICS^R. Log transformations were performed on all data, except percent POM, in order to normalise the data. One-way ANOVA or the Kruskal-Wallis Test (if the variances were not equal) were used to test for significant differences between sites and between seasons.

In order to group the sites with respect to all the variables, the median values for each variable were analysed by Wishart's Clustan Furthurest Neighbour Hierarchical Method (Wishart, 1987), and the results obtained are presented in the form of a dendrogram.

Distances within which recovery occurred were determined by comparing the downstream values to the values for the stream site immediately above the impoundment. If the "above-impoundment" site was itself impacted then the stability of values between two or more downstream sites was interpreted as the new dynamic equilibrium.

RESULTS

Effect of impoundments

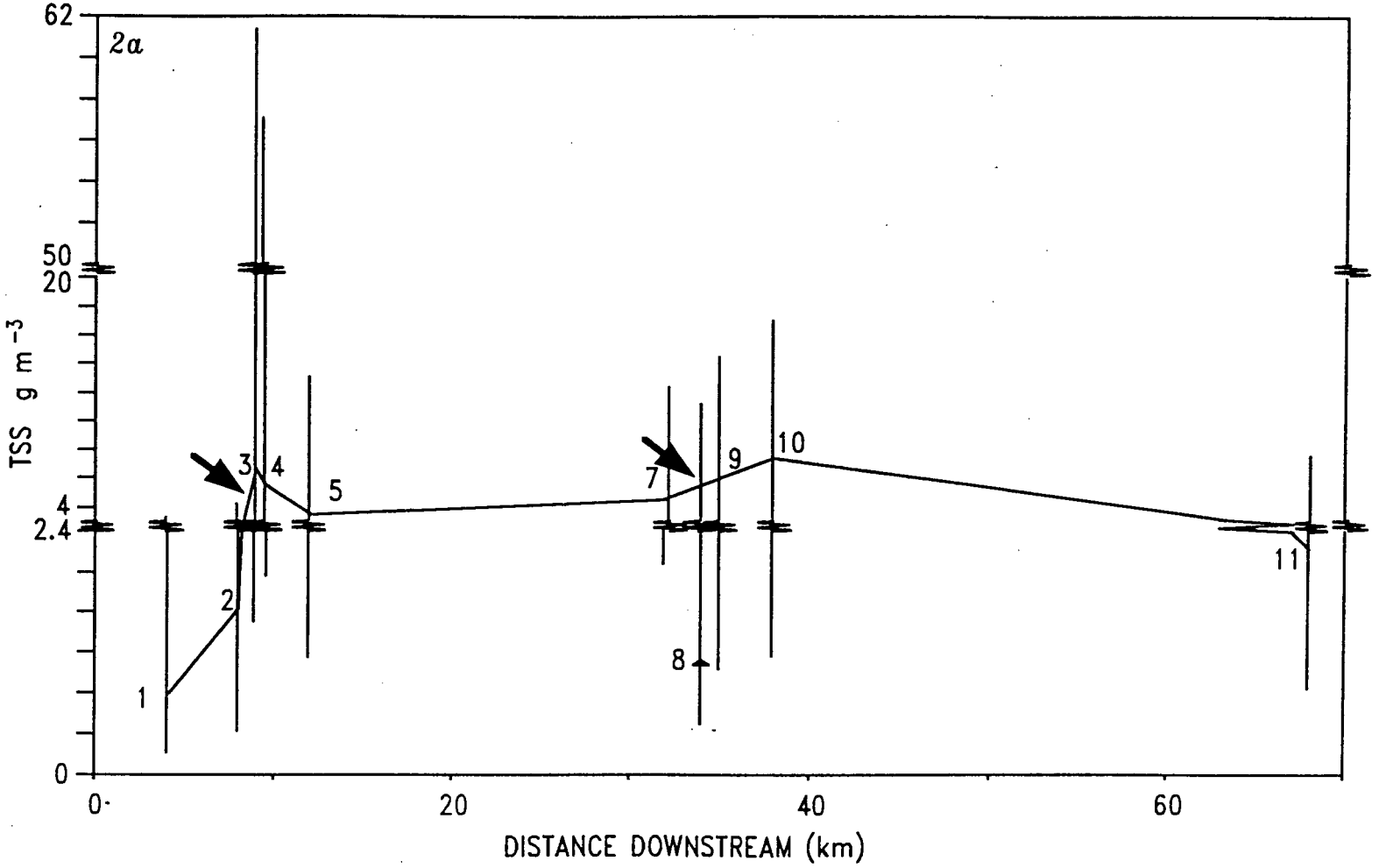
The two impoundments appeared to influence the quantities of transported particulate matter in very similar ways. The median quantities of TSS (Figure 2a) increased from 0.8 g m^{-3} near the source (PR1) to 1.6 g m^{-3} just above Nuweberg (PR2), increasing to 6.6 g m^{-3} below the impoundment. Median quantities of TSS then decreased to 5.5 g m^{-3} within 0.5 km below Nuweberg (PR4) deceasing further over the next 2.5 km to 3.4 g m^{-3} at site PR5. Above Arieskraal the median value for TSS was 4.4 g m^{-3} which increased to

5.9 g m^{-3} below the impoundment increasing further over the next 3 km to 7.4 g m^{-3} at site PR10. Median quantities of TSS then decreased over the next 30 km to 2.2 g m^{-3} at site PR11, just above the estuary. At the site on the tributary, the Klein Palmiet, PR8, the median value for TSS was 1.1 g m^{-3} , similar to the median quantity found in the pristine headwaters at site PR1.

The median percent organics in the TSS (Figure 2b) was high in the pristine headwaters, 82% at PR1, decreased to 60% above Nuweberg (PR2) and decreased further to 46% below the impoundment (PR3). Median percent organics then increased to 55% within the next 0.5 km (PR4) and increased slightly over the next 3 km to 57% at site PR5. Above Arieskraal the median percent organics was 53% (PR7) and decreased to 44% below the impoundment (PR9), decreased further over the next 3 km to 36% (PR10) and then increased over the next 30 km to 52% just above the estuary (PR11). At site PR8 on the tributary the median percent organics value of 65% was lower than the value for the pristine headwaters but higher than was found at any other site on the Palmiet River.

The division of the TSS into different size classes (Figure 3a,b,c,d) showed a substantial increase below both impoundments in the smallest size class (UPM, UPOM & UPIM; Figure 3a(iv), b(iv) & c(iv)) and in the inorganic and organic fractions of the second smallest size class (VPOM & VPIM; Figure 3b(iii) & c(iii)). In all other size classes there was a decrease in quantities below the impoundments. However, for percent organics in the different size classes (Figure 3d) the effects of the impoundments differed below the two reservoirs: Nuweberg showed a predominant decrease in percent organics below the impoundment, except for the coarse size class, whereas Arieskraal showed an increase in percent organics in all size classes except for the smallest fraction (Figure 3d).

The impoundments also resulted in an increase in the proportion of the smallest size class (UPM) of the TSS (Figure 4): UPM comprised 82.5% of the TSS above Nuweberg and 98.5% below the impoundment, 97.6% above Arieskraal and 99.2% below the impoundment. Average annual discharge (Figure 5) was low in the upper reaches (5.3×10^6 m^3 y^{-1} ; PR1), increased from 7×10^6 m^3 y^{-1} above (PR2) to 10.8×10^6 m^3 y^{-1} below (PR3) Nuweberg and decreased from 38.6×10^6 m^3 y^{-1} above to 28.7×10^6 m^3 y^{-1} below (PR9) Arieskraal, increased to 64×10^6 m^3 y^{-1} at


2a
62
50
20
4
2.4
0
TSS g m⁻³
0
20
40
60
DISTANCE DOWNSTREAM (km)
1
2
3
4
5
7
8
9
10
11

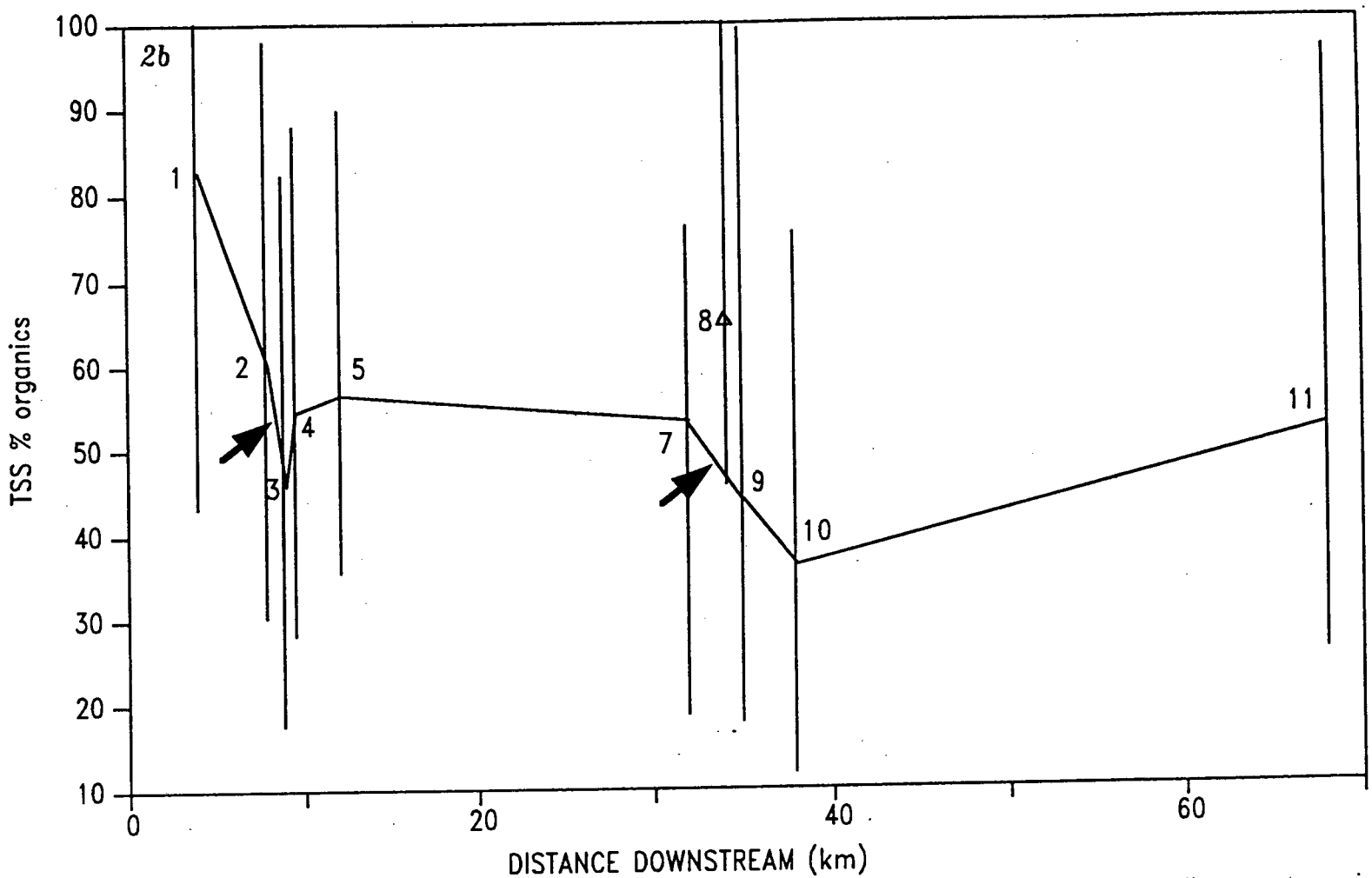
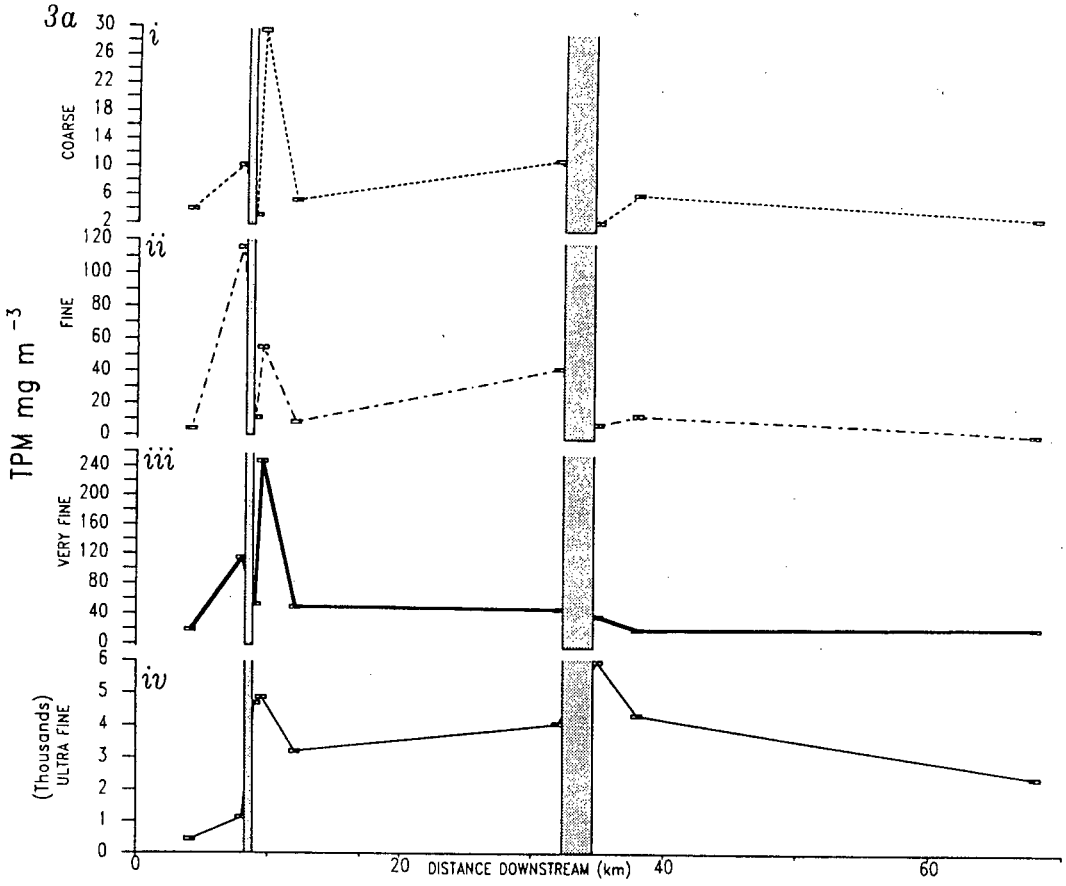
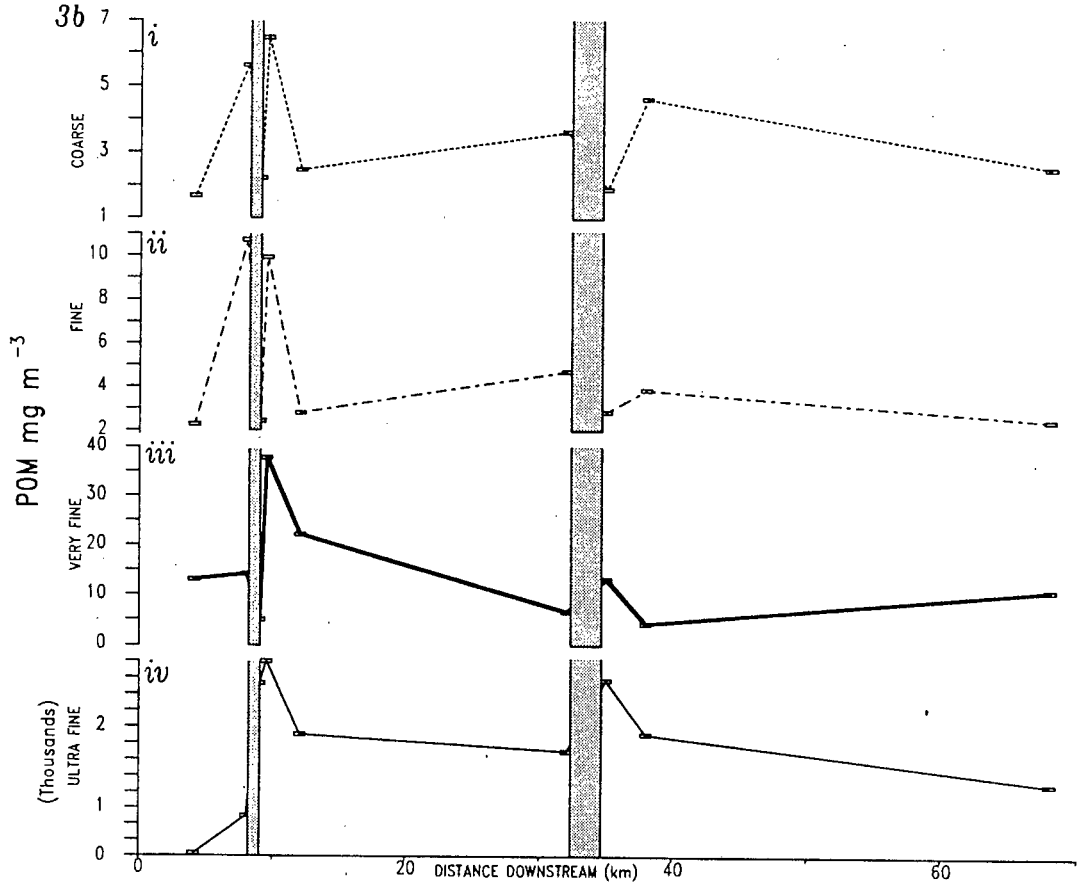
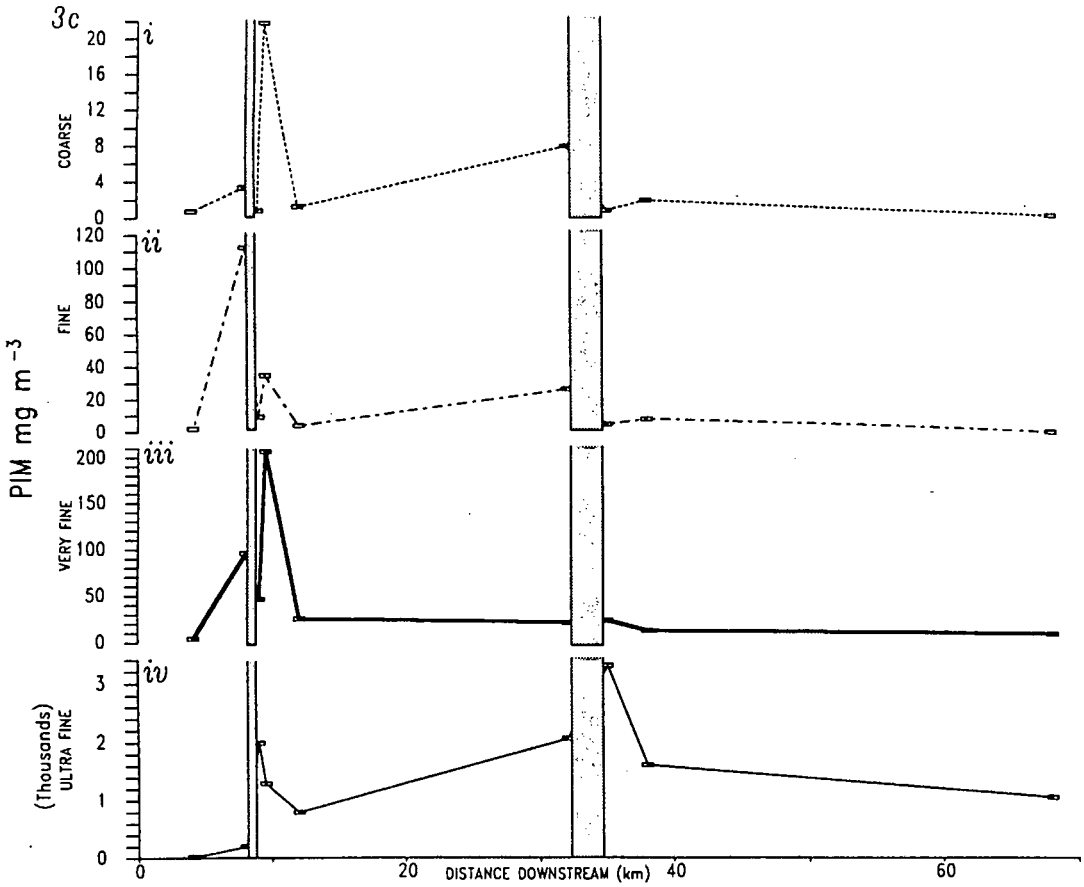


Figure 2: The downstream changes in a) the median quantities of total suspended solids (TSS) and b) the median percent organics in the TSS from the source to the estuary of the Palmiet River. The vertical lines are maximum/minimum lines (i.e. ranges). The arrows indicate the position of the dams, Nuweberg and Arieskraal.


3a
TPM mg m -3
i
COARSE
ii
FINE
iii
VERY FINE
iv
(Thousands)
ULTRA FINE
0
20
DISTANCE DOWNSTREAM (km)
40
60


3b
POM mg m -3
i
COARSE
ii
FINE
iii
VERY FINE
iv
(Thousands)
ULTRA FINE
0
20
DISTANCE DOWNSTREAM (km)
40
60



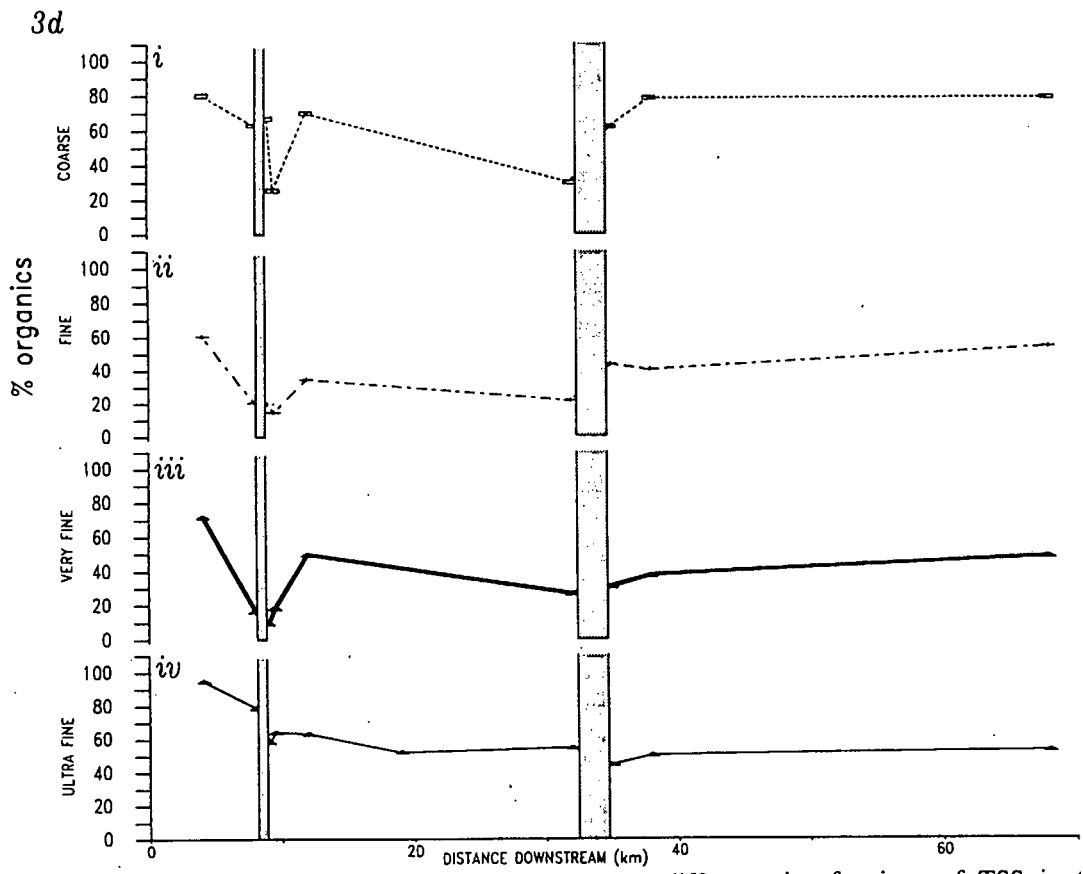


Figure 3: The downstream changes in the different size fractions of TSS in the Palmiet River:

a) Median quantities of total particulate matter
b) Median quantities of organic particulate matter
c) Median quantities of inorganic particulate matter
d) Median percentage organics

The vertical shaded bars represent the two impoundments on the river, Nuweberg Dam and Arieskraal Dam.

site PR10 and increased further to 97 x 10^6 m^3 y^{-1} at site PR11 near the mouth. Suspended particulate loads were also low in the pristine headwaters (0.004 x 10^6 kg y^{-1} ; PR1), increased from 0.01 x 10^6 kg y^{-1} above (PR2) to 0.07 x 10^6 kg y^{-1} below (PR3) Nuweberg and then decreased to 0.02 x 10^6 kg y^{-1} over the next 3 km to site PR5. Suspended particulate loads slightly increased from 0.17 x 10^6 kg y^{-1} above (PR7) to 0.18 x 10^6 kg y^{-1} below (PR9) Arieskraal, increased over the next 3 km to 0.35 x 10^6 kg y^{-1} at site PR10 and then decreased towards the estuary to 0.24 x 10^6 kg y^{-1} at site PR11.

CPOM:FPOM

CPOM:FPOM ratios increased from 0.11 near the source to 0.23 above Nuweberg (PR2), increased further to 0.3 below the impoundment and then decreased to 0.14 at site PR4 and to 0.1 at site PR5, 2.5 km downstream (Figure 6). Conversely, the ratio below Arieskraal decreased from 0.32 above (PR7) to 0.12 below (PR9) the impoundment then increased to 0.58 at site PR10 before decreasing over the next 30 km to 0.2 at site PR11, just above the estuary (Figure 6).

Discharge vs. quantities of suspended solids

Table 2: Significance levels of linear regression analysis between discharge and quantity of particulate matter for all size fractions (C, F, V, U and TOT) of particulate matter (PM), particulate organic matter (POM) and particulate inorganic matter (PIM).

	$p<0.05$	$p<0.005$
PR1	-	-
PR2	CPOM; VPOM	-
PR3	-	-
PR4	-	-
PR5	-	-
PR7	FPOM; TOTPOM VPIM	CPM; FPM; VPM; VPOM; CPIM; FPIM;
PR8	UPM	-
PR9	UPM; UPIM	-
PR10	VPM; VPOM	-

Regression analysis on the entire data set showed no linear relationship between discharge and quantities of TSS. When the data were analysed separately for site and size class, total as well as organic and inorganic fractions (Table 2), site 7 frequently showed significant relationships between discharge and suspended solids, mostly in the larger size classes (VPM, FPM and CPM).

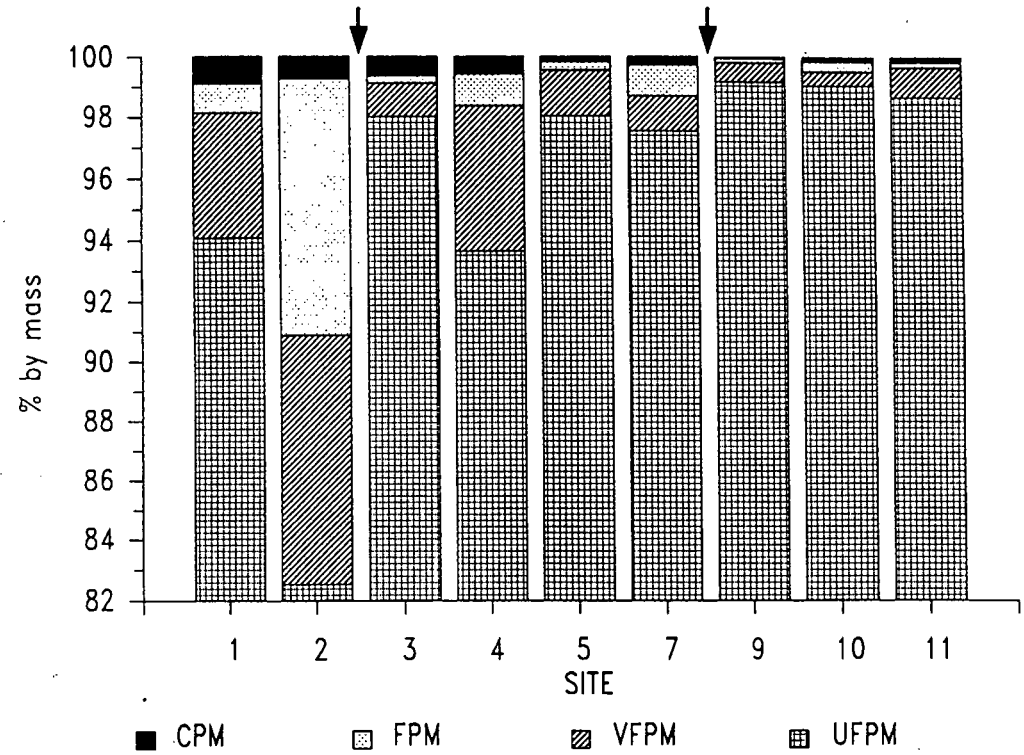


Figure 4: The percentage contribution by mass of the different size classes of particulate matter at each site on the Palmiet River. The UPM comprised from 0-82%+ at all sites. The arrows indicate the position of the dams, Nuweberg and Arieskraal.

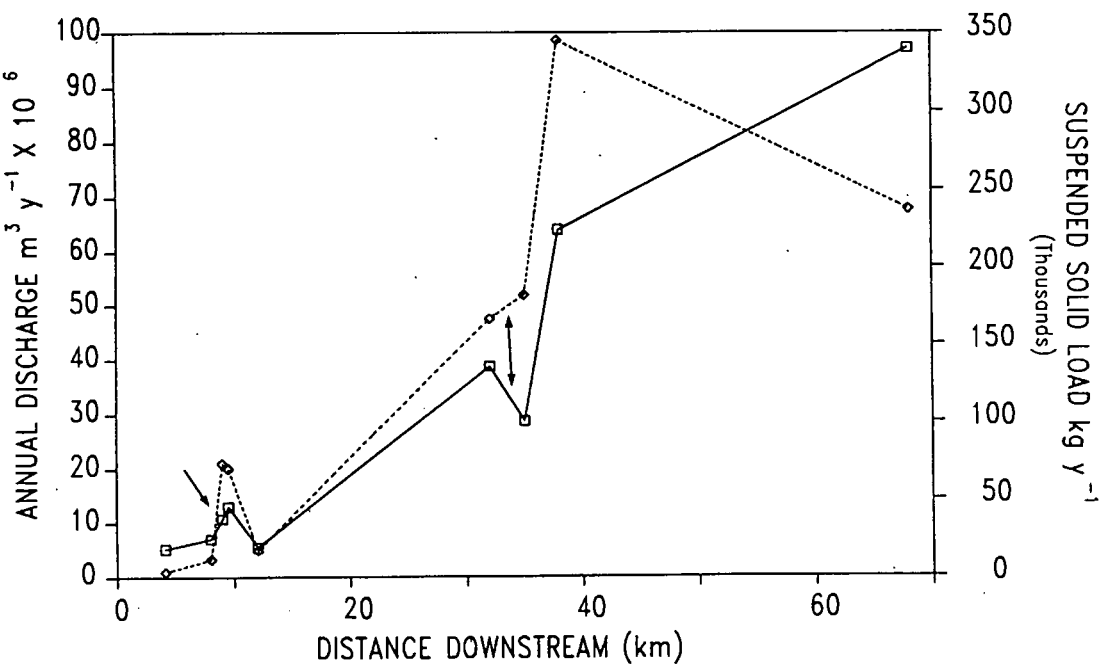


Figure 5: A comparison between the annual discharge at each site (solid line) and the annual suspended solids load at each site (dashed line) on the Palmiet River.

The second smallest size class (VPM, VPOM or VPIM) most often correlated with flow. Sites 1, 3, 4 & 5 showed no correlation at all, whereas the data from sites 2, 9 and 10 showed a positive correlation with discharge in only 2 out of 15 cases and site 8 on only 1 out of the 15 cases looked at (i.e 4 size fractions plus a total for PM, POM and PIM). Annual discharge past each site correlated significantly ($r=0.8487$, $n=9$, $p<0.005$) with annual suspended particulate loads (Figure 7).

Seasonality

Table 3: Significance levels for ANOVA or Kruskal-Wallis analysis to determine whether or not distinctions exist between sites or seasons (*=p<0.05; **=p<0.01; ns=not significant).

SIZE (μm)	SAMPLE	SITE/ SEASON	ANOVA	VARIANCE	KRUSKAL-WALLIS
>950	TOTAL	SITE	*	=	
		SEASON		≠	ns
	%ORG	SITE	**	=	
		SEASON	ns	=	
<950					
>250	TOTAL	SITE	**	=	
		SEASON		≠	ns
	%ORG	SITE	**	=	
		SEASON	*	=	
<250					
>80	TOTAL	SITE	**	=	
		SEASON	ns	=	
	%ORG	SITE		≠	**
		SEASON	ns	=	
<80					
>0.6	TOTAL	SITE		≠	**
		SEASON		≠	ns
	%ORG	SITE	**	=	
		SEASON		≠	**

Statistical analysis (ANOVA or Kruskal-Wallis) of the data showed significant differences ($P<0.05$) between sites for all the different size classes and very few significant differences between seasons (percent organics in the FPM and UPM size classes; Table 3). Analysis of the particulate data, looking at the season in which the maximum value was recorded, however, showed a definite increase in quantities of particulate material in autumn, in 42 out of a total of 44 cases (i.e. 11 sites and 4 size fractions) the maximum occurred in autumn or winter. The highest percent organics occurred predominantly in summer with 28 out of the 44 cases having a maximum in summer or autumn.

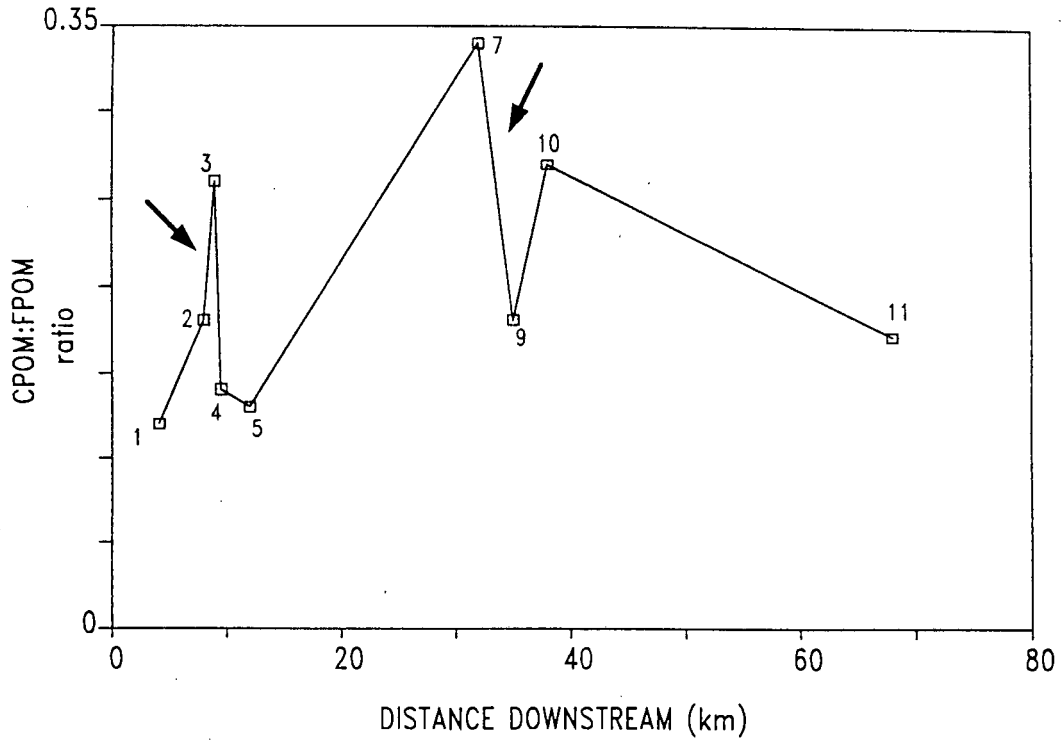


Figure 6: The downstream changes in CPOM:FPOM ratio on the Palmiet River. For this graph the FPOM and VPOM in the present study were combined in order to be comparable with the size classes used by Vannote *et al.* (1980) in the RCC. The arrows represent the positions of the two dams.

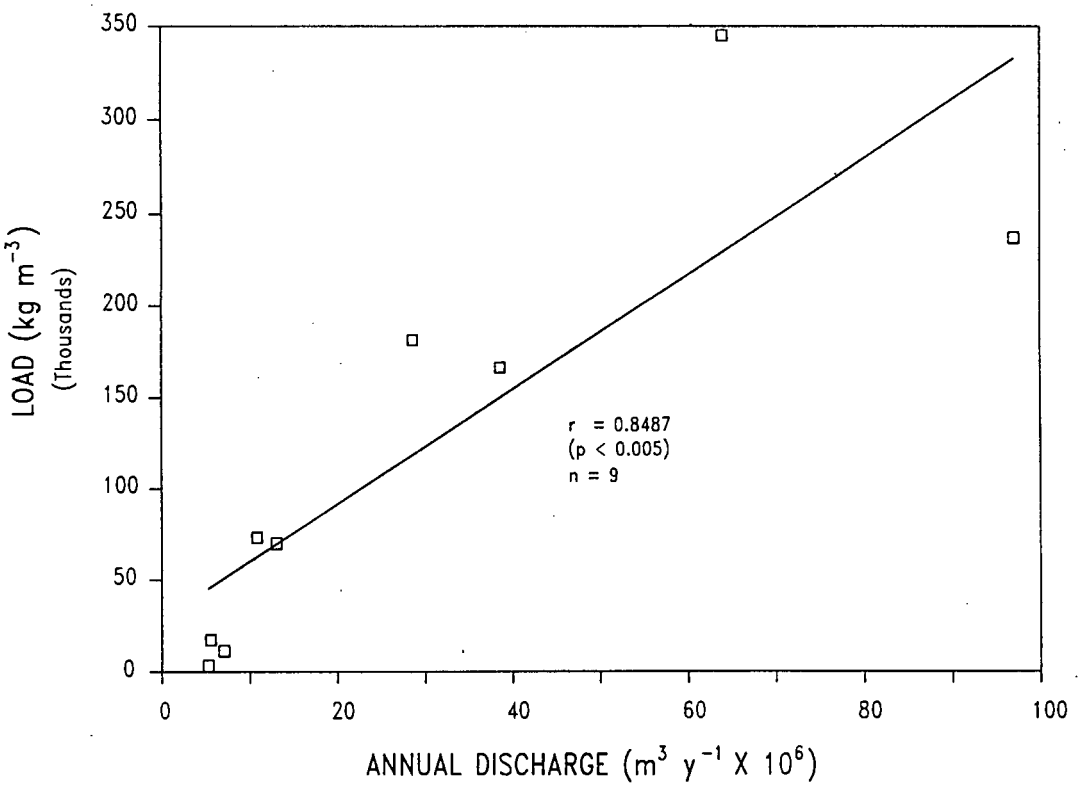


Figure 7: Graph showing the correlation between annual discharge and particulate loads at each site.

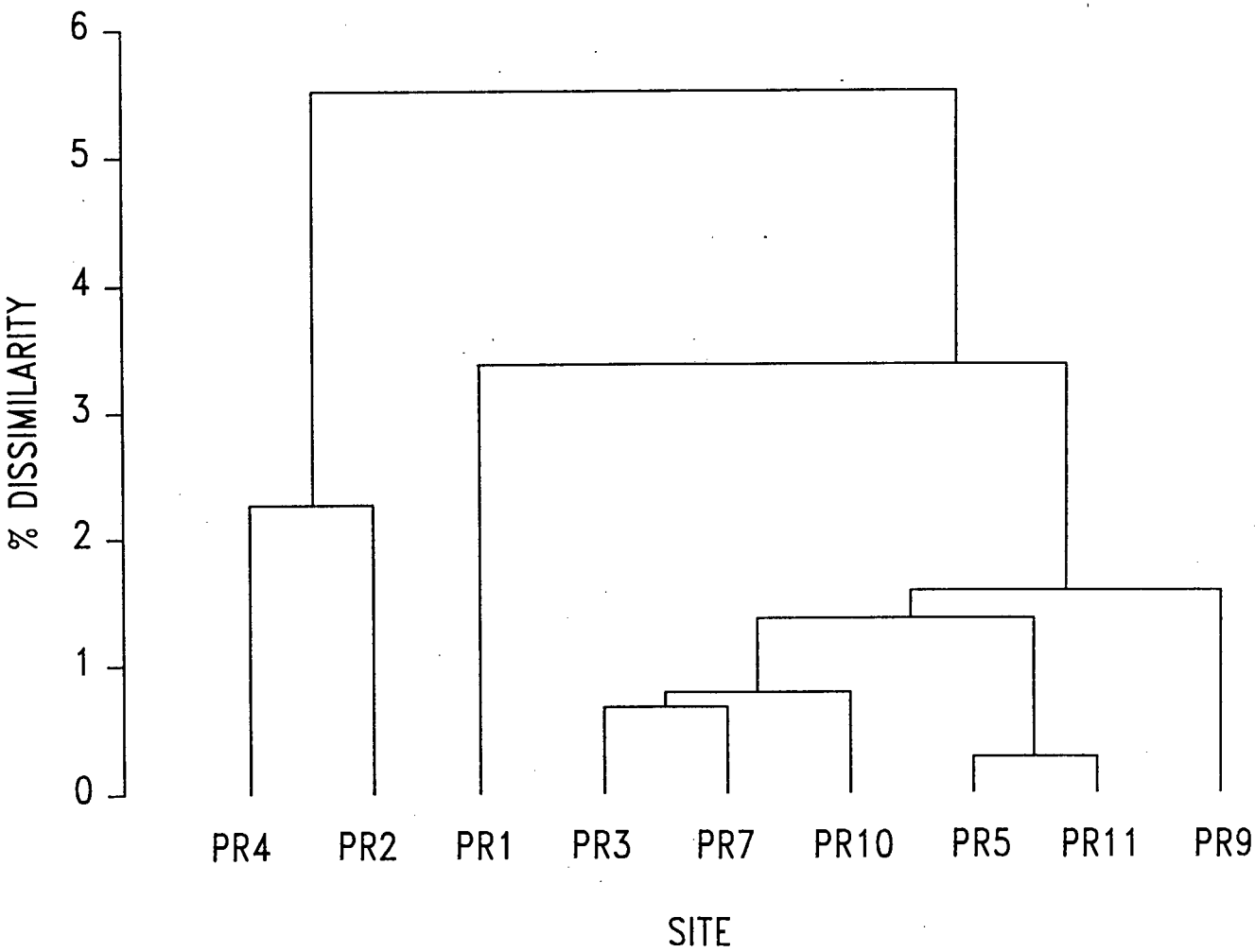


Figure 8: A dendrogram of the similarity between sites on the Palmiet River obtained from the Clustan Furthurest Neighbour Heirarchical Method (Wishart, 1987).

Cluster analysis

A dendrogram (Figure 8) using the median values of the total, organic and inorganic particulates, as well as the CPOM:FPOM, FPOM:VPOM and rest:UPOM ratios, including the maximum density m^{-3} of each zooplankton species (cladocerans, copepods and chaoborids) at each site, divided the sites into three main groups: the sites downstream of the impoundments (sites 3, 5, 7, 9, 10 & 11), those farthest from the impoundments showing the highest degree of similarity (sites 5 & 11); the pristine headwaters (site 1); and the influent water to Nuweberg (site 2) and the site 0.5 km below Nuweberg (site 4).

DISCUSSION

The Palmiet River is a short, clean, cool acid mountain stream with low quantities of suspended solids, which fluctuate greatly down the length of the river. Extremely low quantities of suspended particulate matter were recorded in the upper reaches of the Palmiet (0.8-1.6 g m^{-3}) as compared with, for example, the Buffalo River (3-5 g m^{-3} : Palmer and O'Keeffe, 1990). Low levels of particulate matter, a characteristic of headwater streams (Sedell *et al.*, 1978; Maciolek and Tunzi, 1968), are due to factors such as: efficient retention and processing by the forest and its streams; inputs of large CPOM not easily moved by currents; low nutrient concentrations limiting the development of a large biomass of primary producers; and fast currents or high precipitation eroding the stream bed to cobble or bedrock (Naiman and Sedell, 1979). In the Palmiet River headwaters there is no forest and no canopy cover, the predominant vegetation being fynbos (low shrubland) and thus the main source of CPOM to the stream is probably windblown debris. Low nutrients and fast currents and high rainfall during winter, are a feature of this reach of the river (Byren and Davies, 1989).

General effect of impoundments

The smallest size class of particulate matter (UPM; 0.45 - 80μm) predominates at all sites ranging in proportion from 82% at site PR2 to 99% at sites PR9 & PR10. Small particles are easily moved by water and difficult to trap (Malmqvist *et al.*, 1978; Bilby and Likens,

1979; Naiman and Sedell, 1979) and therefore dominate the particulate matter transported by streams (Britton 1990).

On many rivers, especially those with highly turbid waters, particulates settle out within an impoundment resulting in a decrease in the amount of sediment transported by the effluent water from the reservoir (Petts and Greenwood, 1985; Walker, 1985). This results in the addition of high-energy, low-silt water, sometimes termed "silt hungry", to the system causing extensive erosion of the channel immediately downstream of the impoundment thus rapidly increasing the suspended solids load in the river (Simons, 1979; Webster *et al.*, 1979; Petts, 1984; Gilvear and Petts, 1985; Petts and Greenwood, 1985; Petts and Thoms, 1986; Petts, 1988). In the Palmiet River there is a fairly large increase (compared with upstream quantities) in ultra fine suspended solids below both impoundments, probably due to the generally low quantities of TSS in the river and high turbulence and mixing at the outflow pipes. Suspended solids loads immediately downstream of a reservoir can be derived from in-channel erosion or from the water in the reservoir (Gilvear, 1988). The proportion of ultra-fine material in the transported particulate matter in the Palmiet River was never less than 82% of the TSS and increased to 98% and 99% below Nuweberg and Arieskraal respectively. However, there was a decrease in the percent organics (and, therefore, and increase in percent inorganics) in the ultra-fine size class below both impoundments and thus, the reservoirs on the Palmiet River may be classed as point sources of sediment. Downstream from a point source sediment deposition can be described as an exponential function of distance (Shapley and Bishop, 1965; Mahoney and Eisman, 1984). Reduction to half the initial concentration by deposition is dependent on water depth and settling velocity (Einstein, 1968). A reduction to half the above-impoundment quantities occurs within 3 km below Nuweberg whereas, 3 km below Arieskraal quantities of ultra-fine particulates are almost equivalent to the above impoundment levels.

Downstream of an impoundment the elimination, or reduction in the magnitude and frequency, of mainstream floods, which act as natural 'flushing flows', results in sedimentation in the channel (Petts, 1979; Williams and Wolman, 1984; Petts and Thoms, 1986; Petts, 1988). Current velocity has only a minor effect, except on the distance over which deposition is distributed (Carling, 1984), i.e the recovery distance (sensu O'Keeffe *et*

al., 1990). Tributaries also add to the suspended solids load, and deposition downstream of a tributary confluence is a common occurrence, decreasing channel depth and reducing substratum particle size (Petts and Greenwood, 1985). The highest concentration of fines in river water often occurs within a short reach below tributary confluences (Petts, 1988). The decrease in suspended particulate load 3 km downstream of Arieskraal is probably due to the settling out of reservoir-derived ultra-fine particulate matter as well as tributary-derived particulates, as site 10 is approximately 2.5 km downstream of the confluence of the Palmiet and the Klein Palmiet Rivers. This is in accordance with the findings of Petts (1988), on both the River Daer, Scotland and the River Derwent, England, that the concentration of fines within gravel substrata was elevated between the dam and the tributary confluence and for 2.5 km below the confluence.

Percent organics

The percentage of organics in the coarse size fraction was usually greater than 70% which may be indicative of a current velocity able to transport large organic particles that are generally lighter than large inorganic particles. In the upper reaches of the Palmiet River suspended particulate matter consisted almost entirely of organic matter, whereas towards the lower reaches the particulate matter was only 50% organic. Percentage organic matter usually decreases as particle size decreases but may increase again in the ultra-fine size class (Naiman and Sedell, 1979), although this was not the case in the present study. A decrease in the percent organics in the middle and lower reaches could be indicative of more erodible inorganic material, Bokkeveld shale soils, and the land-use practices (predominantly fruit-farming) in the middle section of the catchment, as well as processing of organic material by macroinvertebrates and micro-organisms within the river (Maciolek and Tunzi, 1968; Vannote *et al.*, 1980).

Gilvear and Petts (1985) maintain that fine organic matter ($<20\ \mu m$), largely of allochthonous origin, predominates immediately below an impoundment, but that the inorganic fraction dominates (90% $<10\ \mu m$) within 3 km. Below the impoundments on the Palmiet River the percent organics in the ultra-fine size class decreases and subsequently increases over the next 3 km. This is probably due to the resuspension of inorganic silts and clays as a result of outflow turbulence. The difference in coarse, fine, and very-fine percent

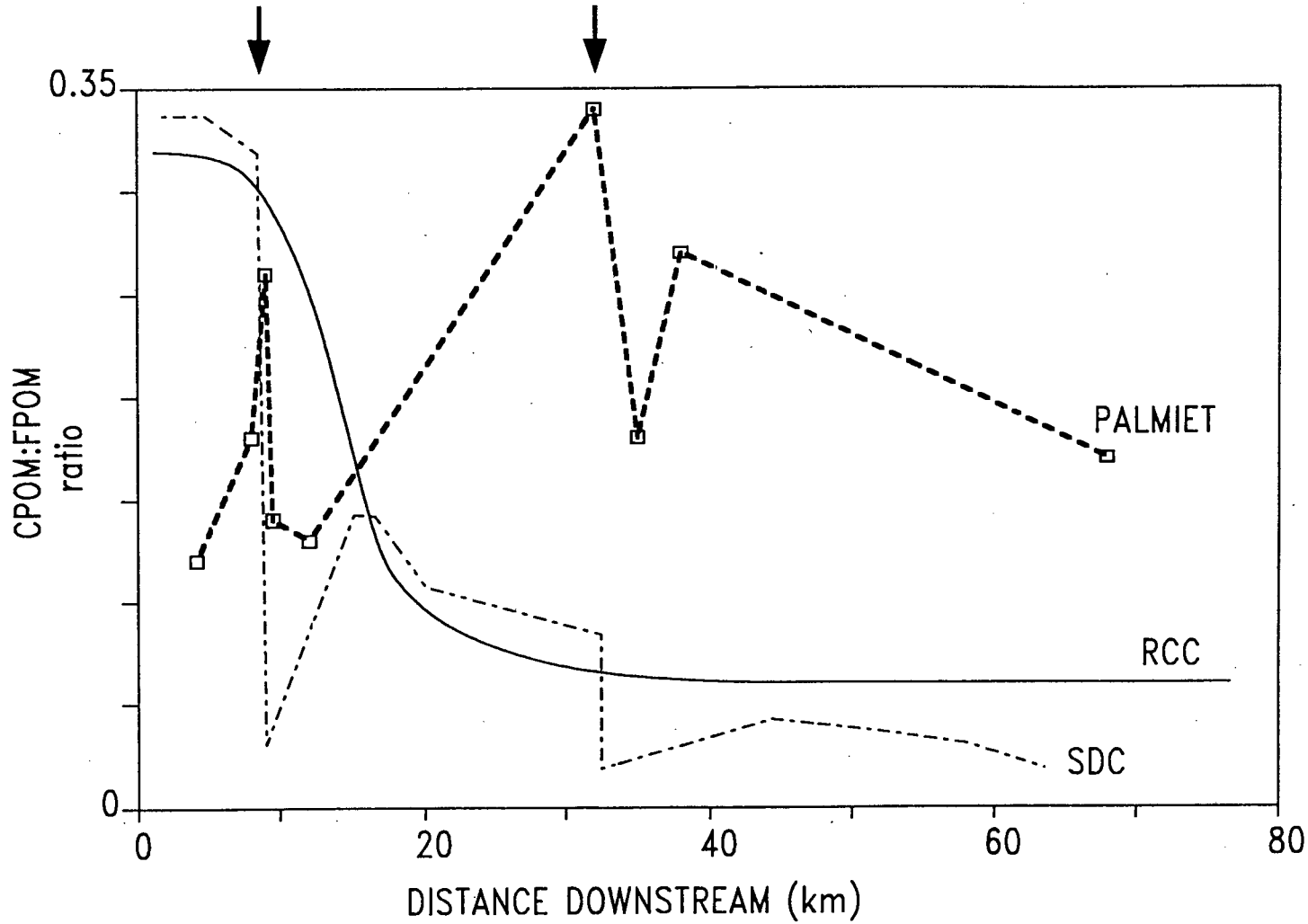


Figure 9: A comparison between the trends predicted by the RCC (solid line) and the SDC (dot-dash line) for downstream changes in CPOM:FPOM ratios and the actual values obtained for the Palmiet River (thick dashed line).

organics below the two impoundments on the Palmiet River is probably related to canopy cover immediately below each impoundment and to the pattern of release of water from each reservoir. Below Nuweberg the reduced input of allochthonous organic material and the release of high-energy water, particularly during summer (it is an irrigation supply impoundment), probably picks up larger inorganic particles. Below Arieskraal there is greater input of organic allochthonous material from riparian vegetation (alien *Pinus* spp) and flow rate is more constant (Byren and Davies, 1989).

CPOM:FPOM ratio

The general trend of CPOM:FPOM (excluding the influence of the impoundments i.e. using sites which are unaffected by dams or where recovery has occurred) does not compare well with that predicted by the RCC (Figure 9). The RCC (Vannote *et al.*, 1980) predicts that the ratio of CPOM:FPOM will decrease as stream order increases (ignoring the very small headwater streams, which lack the power to move even small particles, thus having a very low ratio of CPOM:FPOM: Cummins, 1975, 1977). Although the RCC and SDC do not provide actual values for the x and y axes, for comparative purposes the trends hypothesised in the RCC, as interpreted by Ward and Stanford (1983a), and the SDC have been superimposed on the results obtained for the Palmiet River. In the Palmiet River the CPOM:FPOM ratio is low in the headwaters (4 km from the source), increases slightly over the next 4 km and, ignoring the effect of the impoundments, appears to remain constant to the estuary i.e a ratio of 0.18 $\pm$8 km from the source compared with 0.175 $\pm$3 km above the estuary. The RCC is based on the assumption that heavily shaded forests receive greater quantities of large organic particles, while small organic particles usually occur in greater quantities in higher order streams. Naiman and Sedell (1979) found this not to be true for their four study streams in the Cascade Mountains, USA, however. The RCC appears to imply that all headwater streams are canopied and therefore should have a high CPOM:FPOM ratio, and should function in a specific manner. The Palmiet River does not have a canopied headwater reach, a factor common in many streams in the south-western Cape and therefore, will have a totally different CPOM:FPOM ratio than that predicted by the RCC.

The headwaters of the Palmiet River have a very low ratio of CPOM:FPOM and are characterised by an absence of debris dams and leaf-packs (B. A. Byren-Gale, pers. obs.), indicative of the lack of allochthonous input into the system. Britton (1990) found that a forested headwater tributary, Swartboschkloof, in the south-western Cape, South Africa, was highly retentive of CPOM and Bormann *et al.* (1969) showed that POM is trapped and metabolised in the headwaters of their New Hampshire study stream. Headwater streams in temperate forested regions retain CPOM inputs and primarily export smaller particles (Boling *et al.*, 1975; Naiman and Sedell, 1979; Webster and Patten, 1979; Wallace *et al.*, 1982; Kazmierczak, *et al.*, 1987) probably due to the low stream power which is unable to transport large organic material. Naiman and Sedell (1979) suggested that various factors could affect CPOM:FPOM ratios including the physical size of biotic inputs; stream power available to move organic material; and the ability of retention structures to slow downstream movements of those inputs. Results from the Palmiet river thus support the conclusion of Naiman and Sedell (1979) that stream order alone is not a good indicator of CPOM:FPOM ratios since all streams export mostly small-sized particles, and larger sized particles are also often transported when retention structures are absent or altered.

The SDC predicts that the ratio of CPOM:FPOM will decrease below both an upper- and a middle-reach impoundment, the decrease being more marked below the upper-reach impoundment. The effect of impoundments on the Palmiet River compares well with the predictions of the SDC below the middle-reach impoundment, Arieskraal, but not so well directly below the upper reach impoundment, Nuweberg (Figure 9). Immediately below Nuweberg the ratio of CPOM:FPOM increases due to a large decrease in the FPOM and a relatively smaller decrease in CPOM. The ratio of CPOM:FPOM then decreases rapidly within 0.5 km (Figure 6) and decreases further over the next 3 km as the water deposits larger particles and picks up smaller particles. The decrease in the quantities of the larger size fractions below the impoundments of the Palmiet River indicates a settling out of larger particles within the impoundments. Quantities of CPOM are usually reduced below impoundments since instream transport from upper reaches is eliminated (Ward, 1976) and thus CPOM transported from upstream probably only plays a minor role in the energetics of regulated-stream reaches (Short and Ward, 1980).

Discharge vs. quantities of suspended solids

Some authors have found a direct relationship between particle concentration and discharge (Wolman and Miller, 1960; Bagnold, 1966; Bormann *et al.*, 1974; Webster and Patten, 1979; Webster, 1983), whereas this relationship was rarely found for the Palmiet system (Table 2), probably due to the time and frequency of sampling. Fisher and Likens (1973) showed that FPOM concentration was higher for a given discharge on the rising limb of a hydrograph than it was on the falling limb which indicates that the actual time of sampling is important. Kazmierczak *et al.* (1987), working on the New River, USA, found it difficult to predict transport during most discharge conditions and suggested that in some systems, seston concentration and transport may be less a function of discharge and power than of the effects of long-term seasonal and short term discharge cycles on the density and size characteristics of seston. The complex relationship between transport and discharge is directly influenced by entrainment and deposition (Kazmierczak *et al.*, 1987). Seston concentration and transport in most lotic systems cannot be reliably predicted based solely on measurements of discharge. Highly variable particle densities can drastically alter rates of entrainment even if particle size distributions remain constant (Kazmierczak *et al.*, 1987). Britton (1990) showed that for Swartboschkloof, a small, forested, mountain stream, concentrations of POM in drift samples were influenced by discharge, although no significant relationships were detected between discharge and any of the size fractions. Bilby and Likens (1979) concluded that the quantity of fine particulate organic carbon (FPOC) in stream water is dependent not only on discharge but also on the amount of FPOC on the stream bed (and possibly in the canopy) and the duration of dry weather before rain events (see also Britton, 1990). The data in the present study show a highly significant relationship ($p < 0.005$) between annual discharge at each site and annual suspended particulate load at each site. The warning by Carling (1988), that each reservoir/catchment system is unique, producing singular responses that cannot easily be integrated into a basic general model, except at a facile level, is noted and should be heeded, however.

Seasonality

Naiman and Sedell (1979) maintain that diel variations in organic matter concentration are seldom regular or of sufficient magnitude to be considered periodic. The transport of particulate matter in streams is known to show seasonal variations however, because the

inputs of litter are often seasonal, as is the conversion of large organic particles to smaller ones that can be transported under lower flow conditions; and the volumes of precipitation which supply water to surface drainage systems also vary seasonally in many regions (Dance, 1981). Bormann *et al.* (1969) showed that a very large proportion of organic matter left a woodland stream in New Hampshire during spring runoff. Autumn-shed leaves are a common source of allochthonous particulate matter in temperate Northern Hemisphere streams (Naiman, 1976; Kazmierczak *et al.*, 1987); in the south-western Cape of South Africa, however, leaf fall occurs in spring/summer at the beginning of the season of highest temperatures and lowest flows. Thus allochthonous organic material may remain on the stream bed, undergoing breakdown for many months before being flushed out during high autumn/winter flows (King *et al.*, 1987), resulting in the observed predominance of particulate material in suspension in the Palmiet River during autumn/winter. On the other hand, the lowest percentage organics (i.e. highest percentage inorganics) also occurred in autumn/winter probably due to inorganic runoff (Maciolek and Tunzi, 1968) and streambed flushing during the rainy season (April to September). The highest percent organics occurred in summer as a result of to spring/summer leaf fall and of the very low flow volumes, which reduce the stream's ability to transport heavy inorganic particles.

Zooplankton

The idea that zooplankton concentrations could form a large and important contribution to POM below impoundments was first promoted by Chandler (1937) and reiterated by Gilvear (1988). The biomass of lake-derived zooplankton below Nuweberg and Arieskraal has been calculated from the densities of cladocerans, copepods (biomass figures from Hart, 1986) and phantom midges (*Chaoborus* sp; biomass measured) found in the invertebrate drift. Rotifers were excluded as sampling only included fauna retained by a 250 μm sieve. The biomass of lake-derived zooplankton proves to be less than 0.1% of the total mass of suspended particulate matter transported, agreeing with Maciolek and Tunzi (1968), who have indicated that the presence of mineral and organic detritus always surpasses the plankton in quantity (Welch, 1952; Cushing, 1964). Furthermore, Cellot and Bournaud (1984), working in the Jons area on the Rhône River, upstream of Lyons, France, found 9.6 t y^{-1} macroinvertebrates compared with 400 000 t y^{-1} of total suspended solids.

Benthic macroinvertebrates

The effects of downstream changes in suspended particulate loads on benthic macroinvertebrate communities have been widely researched and results have varied greatly. Cordone and Kelly (1961), amongst others, maintain that it has long been established that even small increases in the levels of intergravel fines may be detrimental to aquatic resources in general. DeBrey and Lockwood (1990) showed, however, that the addition of a broad size-range of sediment apparently diversified the habitat and Petts (1980) stated that the creation of new relatively fine sediment habitats, resulting from localised siltation, may increase habitat diversity within the overall length of gravel-bed river affected by flow regulation. Walker (1985) inferred that channel changes related to sedimentation of gravel were associated with a temporary period of enhanced species diversity preceding the initiation of channel change, and Gray and Ward (1982) showed that changes in benthic populations (some species increased and others decreased in density) were highly correlated with increases in suspended solids. Barton (1977) and Cline *et al.* (1982) found no substantial long-term impacts on the aquatic macroinvertebrates as a result of the addition of sediment due to construction activities. Workers on the seasonal occurrence and distribution of the invertebrate fauna of streams and rivers in South Africa have concluded that silt, sand and turbidity play an important part in the seasonal distribution of the fauna (Harrison and Elsworth, 1958; Harrison, 1961; Oliff, 1960; Oliff and King, 1964). Chutter (1969) showed that some of the animals adversely affected by silt and sand appeared in large numbers below impoundments in which silt and sand would settle. The decrease in taxonomic richness and increase in density of collectors below the impoundments of the Palmiet River (Paper IV, this thesis) could be indicative of the increase in the quantity of UPM below the impoundments.

Cluster analysis

Quantification of the transport of suspended particulate matter in the Palmiet River indicates the effects that regulation has had on the stream. Cluster analysis of all the variables with respect to site (Figure 8) clearly identifies the sites immediately below impoundments, PR3 & 5 (below Nuweberg), PR7 (below Kogelberg, see study area) and PR9, 10 & 11 (below Arieskraal) as distinctly different from the rest, with the sites farthest downstream from each impoundment PR5 & PR11 being the most similar. The pristine headwater site (PR1) is

identified as completely different from all other sites. Distances within which recovery occurred (Table 4) were variable but in general the downstream effect of Nuweberg and the characteristics of the reach below the impoundment were such that recovery was incomplete before the river flowed into the next impoundment, Eikenhof. Arieskraal, on the other hand, showed a characteristic response to regulation (as discussed above), and the long reach of unperturbed river between the impoundment and the estuary resulted in a high degree of recovery.

Table 4: Distances (km) within which recovery occurred, based on the median values for the particulate variables studied, below the upper-reach (Nuweberg) and middle-reach (Arieskraal) impoundments on the Palmiet River. (p=only partial recovery occurred within the distance given)

	DISTANCES (km)	
	Nuweberg	Arieskraal
Particulates:		
TSS	none	30
CPM	3 p	30
FPM	3	30
VPM	3	30
UPM	3 p	30
CPOM	3	30
FPOM	3	30
VPOM	3 p	30
UPOM	3 p	30
CPIM	3	30
FPIM	3	30
VPIM	3	30
UPIM	3 p	30
% Organics:		
CPM	3	30
FPM	3 p	30
VPM	3 p	30
UPM	none	30
CPOM:FPOM	none	30
% composition	none	30

CONCLUSION

In 1980, Short and Ward stated that the proliferation of dams necessitated a fuller understanding of the effects of stream regulation and provided a setting for testing and developing basic theories of stream ecology (Short and Ward, 1980). This study has attempted to assess the validity of certain tenets of the RCC and the SDC and has discussed the downstream changes in the transport of particulate matter below two impoundments on

the Palmiet River, south-western Cape, South Africa. The changes in the ratio of CPOM:FPOM along the river, the changes in the transport of particulate matter induced by the impoundments and the distances within which recovery occcurred in the Palmiet River have shown that the RCC and SDC apply to certain sections of the river but not to others. The RCC has been criticised as far as its applicability to Southern Hemisphere streams is concerned (Winterbourn *et al.*, 1981, Winterbourn, 1982), but most importantly it must be acknowledged that conditions are often very localised and large differences can exist in the amount and type of particulate matter transported at different stations on the same stream (Dance *et al.*, 1979). Thus, the use of theories and models to predict ecosystem response to perturbation, in order to manage river systems, must be approached with great caution (e.g. Carling, 1988).

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MACROINVERTEBRATE DRIFT DOWNSTREAM OF TWO IMPOUNDMENTS ON A REGULATED RIVER, SOUTHWESTERN CAPE, SOUTH AFRICA.

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MACROINVERTEBRATE DRIFT DOWNSTREAM OF TWO IMPOUNDMENTS ON A REGULATED RIVER, SOUTH WESTERN CAPE, SOUTH AFRICA.

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ABSTRACT

The study, undertaken over a 2 year period, was aimed at understanding the general patterns of macroinvertebrate drift in a cold, blackwater, Southern Hemisphere, mountain stream. The study was also designed to test the validity of the Serial Discontinuity Concept (SDC) with respect to the influence of artificial regulation on drift biotic diversity (interpreted here as taxonomic richness) and zooplankton abundance. Drift samples were taken bimonthly, from April 1986 to April 1988. A total of 36 taxa was recorded of which seven predominated: 4 benthic taxa (Ephemeroptera, Simuliidae, Chironomidae and Oligochaeta) and 3 zooplankton taxa (Cladocera, Copepoda and Chaoboridae). The values of the variables downstream of the impoundment are said to increase or decrease with respect to the "above impoundment" values. Below the upper-reach impoundment (Nuweberg), median drift density increased from 66 to 550 individuals m^{-3} and median drift biomass increased from 4 to 6 mg m^{-3}, both variables subsequently decreasing to below source levels within 3 km. Below Arieskraal (a middle-reach impoundment) median drift density increased from 83 to 224 individuals m^{-3} subsequently decreasing to 71 individuals m^{-3} within 3 km, while median drift biomass increased from 1.44 to 2.02 mg m^{-3} and then decreased to 0.77 mg m^{-3} over the next 3 km. Taxonomic richness of drifting invertebrates decreased from 26 to 17 taxa below Nuweberg and only recovered partially over the 5 km before entering the next impoundment. Below Arieskraal drift taxonomic richness decreased from 22 to 15 taxa and did not return to the above impoundment value before reaching the estuary. Impoundments introduce a large quantity of limnoplankton into the stream ecosystem and severely alter normal stream drift patterns in several unpredictable ways depending on reservoir size, dam outflow mechanisms and the existence of other perturbations downstream. The effect of these impoundments on neither plankton concentration nor (drift) biotic diversity (i.e. taxonomic richness) correspond well with the predictions of the SDC.

INTRODUCTION

The phenomenon of aquatic invertebrate 'drift', the downstream transport of aquatic organisms in the current, was discovered accidentally in the earlier part of this century by scientists (e.g. Needham, 1928) who were interested in the fate of terrestrial insects falling into streams (Brittain and Eikeland, 1988). However, it was only in the 1950s, owing to the work of Müller (1954), that the importance of drifting organisms in lotic ecosystems

Eikeland (1988) cautioned that although these categories may have been useful in the past, they have resulted in a tremendous amount of confusion as regards invertebrate drift. Since several authors have cautioned against the use of classificatory terms for stream drift, no attempt has been made in this paper to assign drift to specific categories.

In South Africa, few projects on stream ecosystem functioning have incorporated studies on invertebrate drift. In the 1970s Chutter (1972) studied *Simulium* drift as part of a general study on the biology of South African Simuliidae. Chutter (1975) looked at the day-time drift in the Mlaas River in Natal to determine distances travelled by drifting larval blackflies. Drift studies have also formed a major part of programmes undertaken by the Freshwater Research Unit at the University of Cape Town on tributaries of the Eerste River in the south western Cape (Langrivier - Raubenheimer, 1987; Douie, 1988; King *et al.*, unpubl. data and Swartboskloof - Britton, unpubl. data). Drift data were also collected as part of a project on the Buffalo River in the Eastern Cape (O'Keeffe and Palmer, unpubl. data). The Buffalo River project was designed as a sister project to the present study in order to compare the effects of impoundment on two different river systems (Palmer and O'Keeffe, 1989; O'Keeffe *et al.*, 1990; Palmer and O'Keeffe 1990a,b,c; Palmer, 1991).

The Serial Discontinuity Concept (SDC) of Ward and Stanford (1983) proposes that impoundments cause interruptions in the natural longitudinal gradients of physical, chemical and biological variables in stream ecosystems (*sensu* the River Continuum Concept (RCC) of Vannote *et al.*, 1980). These interruptions in the river continuum may have a recovery or 'reset' distance (*sensu* O'Keeffe *et al.*, 1990) downstream of the impoundment for the river to return to the pre-impoundment continuum or to reach a new dynamic equilibrium. The RCC and SDC are concepts which, although about ten years old, have only been tested in some of the many different types of stream ecosystems around the world. Much controversy has centred around the applicability of the RCC to Southern Hemisphere streams (Winterbourn, 1981; Barmuta and Lake, 1982; Winterbourn *et al.*, 1982) but the SDC has yet to be extensively tested. The SDC discusses two variables which are applicable to macroinvertebrate drift: biotic diversity and plankton abundance. Biotic diversity, which could include species or taxonomic richness, or some form of diversity index, is not defined in the SDC and therfore, for the purposes of this paper, I have

interpreted biotic diversity as taxonomic richness. Recovery distance with respect to plankton is defined as the distance downstream of the impoundment for 95% of the plankton to fall out of suspension (*sensu* Palmer and O'Keeffe, 1990). Since neither the RCC nor the SDC discuss patterns of invertebrate drift *per se*, this study will also add to the understanding of the effect of regulation on macroinvertebrate drift abundance and species composition, in an acid, blackwater, Southern Hemisphere, mountain stream.

Since the programme involved sampling an entire catchment it was only possible to take small samples of daytime drift as part of the collection of transported particulate matter. It is accepted that this is not a representation of "true drift", as diel changes were not assessed, but it was felt that the information obtained was sufficient for an assessment of the effects of impoundment on "background drift". The aim of this study therefore, was to determine the general pattern of background macroinvertebrate drift in the Palmiet River and to examine the possible influences of stream regulation by impoundments on those drift patterns. The study was also designed to test the validity of the predictions of the SDC concerning biotic diversity (i.e taxonomic richness) of drifting organisms in a cool, blackwater, mountain stream.

STUDY AREA

The 74 km long, cool, clear, acid, blackwater Palmiet River (Figure 1), described in more detail in Byren and Davies (1989), rises in the Hottentots Holland mountain range in the south-western Cape, drains a catchment of approximately 500 km^2 (Clarke 1989) and enters the sea between the coastal towns of Betty's Bay and Kleinmond (Figure 1). The river water has low concentrations of nutrients and low quantities of suspended particulate matter, except in the middle reaches where agricultural runoff causes substantial increases in these variables (Byren and Davies, 1989; Paper II, this thesis). The mean annual runoff (MAR) from the catchment is around 245 x 10^6 m^3 (DEA, 1982), and the flow rate varies from 0.02 to 1.0 m^3s^{-1} in summer and from 0.32 to >4.0 m^3s^{-1} in winter (Byren and Davies, 1989). The climate is mediterranean with a strongly seasonal winter rainfall. The riparian vegetation predominantly comprises open canopied fynbos (a low, fire-adapted, macchia-

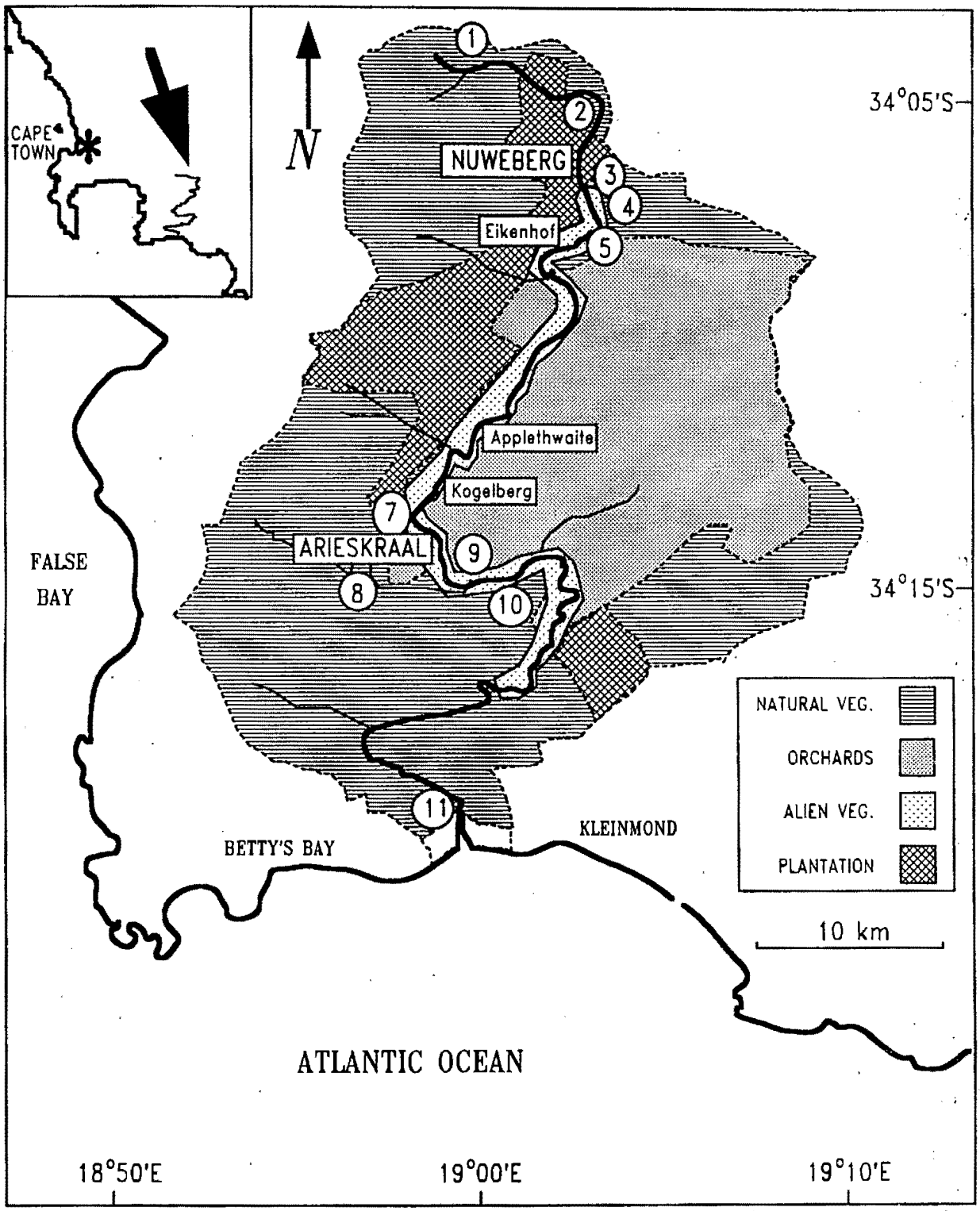

Figure 1: Map of the Palmiet River catchment showing the location of the dams (names in blocks), study sites (numbers in circles) and the main types of surrounding vegetation.

like, shrubland similar to that found in other mediterranean climates) in the upper and lower reaches, and a dense, closed canopy (mainly of alien vegetation - *Acacia* spp. and *Pinus* spp.) in the middle reaches.

The river is impounded five times within the first 40km. Two of the five impoundments were chosen for this study, the uppermost, Nuweberg, and the lowermost, Arieskraal, as the unregulated reach downstream of each of these impoundments was of sufficient length (7 km and 37 km, respectively) to allow recovery distances to be investigated (O'Keeffe *et al.*, 1990). Nuweberg, approximately 9 km from the source, has an earth-fill wall about 25 m high with a bottom release outlet valve about 5 m above the river bed and a maximum capacity of 3.9×10^6 m^3 (Clarke 1989). Arieskraal, about 32 km from the source, has a 26 m high concrete wall and a maximum capacity of 5.9×10^6 m^3 (Clarke 1989). The outlet structure consists of a 40 cm diameter flanged bottom release outlet valve (approx. 15 cm permanently open) about 2 m from the river bottom. Eleven sites were chosen down the length of the river: one in the pristine headwaters (PR1), one above (PR2) and 3 sites below Nuweberg (PR3 - 5), and one above (PR7) and 3 sites below Arieskraal (PR9 - 11). A site (PR8) on a tributary, the Klein Palmiet, was also selected, as water is directly abstracted from the tributary into Arieskraal, and because the tributary enters the river approximately 0.5 km below Arieskraal and could affect recovery distances in the downstream reaches.

METHODS

Drift samples were taken monthly, from April 1986 to April 1988, using an 80 μm-mesh net with a mouth opening of 0.048 m^2 and a tail of 0.5 m, just below the water surface, for between 5 and 10 minutes, depending on the rate of clogging (Douie, 1988). A Zeiss Ott C2 current meter was placed at the mouth of the net to record flow rate through the net so that the total volume of water passing through the net could be calculated. This method was used to collect the transported particulate matter samples (Paper II, this thesis) and the drift fauna collected was a bonus to the overall study. In June/July 1986 most samples could not be obtained because the river was dangerously in spate.

Drift-net samples, one sample per site, were preserved in 5% formalin and returned to the laboratory for processing. Once the samples for 1986 were processed time and manpower constraints dictated that only bimonthly samples for 1987 and 1988 were processed. In the laboratory the samples were split into two size fractions (250 - 950 μm, and >950 μm), and stored in 1% phenoxitol. Macroinvertebrates were removed from the entire coarse fraction (>950 μm) and from a subsample (where necessary) of the fine fraction (250 - 950 μm), identified and counted. Macroinvertebrates were grouped mainly into major taxonomic groups except where a known genus was present (eg. *Hydra*). Since the community structure of the benthic macroinvertebrates (Paper IV, this thesis) and of the zooplankton in the reservoirs (Paper V, this thesis) is known, and the densities of the benthic invertebrates in the drift were very low, it was decided to concentrate on the major taxonomic groups occurring in the drift. The remaining material was analysed for total suspended particulate matter (Paper II, this thesis).

The drift-net mouth area, the speed of water through the net and the time over which the sample was taken were used to calculate the volume of water sampled. Macroinvertebrate densities for each taxon at each site are presented as no. of individuals m^{-3} of water, calculated from the numbers of individuals per sample divided by the volume of water sampled (m^3). The effect of seasonal differences in drift abundance as well as the possibilty of sampling high or low density plugs of water, especially in the reservoir outflow, resulted in a decision to use median values per station, calculated from all the monthly samples during the study period. Median values represent a good indication of base-flow trends and are least affected by extremes (Byren and Davies, 1989; O'Keeffe *et al.*, 1990). The median density per taxon per site is illustrated graphically to indicate broad changes down the length of the river as well as the general effect of the two impoundments. Median biomass was calculated using the median density per taxon per site and values of dry mass per animal obtained from Hart (1986), Stewart and Davies (1986) and J.M. King (unpubl. data). In order to determine the effect of an impoundment on the downstream reaches of the river it was assumed that the river immediately above the impoundment approximated the natural, unperturbed system. The values of the variables downstream of the impoundment are said to increase or decrease with respect to the "above impoundment" values.

Monthly data (not median values) were grouped either by site or by season (winter = June - August, spring = September - November, summer = December - February, autumn = March - May) and using STATGRAPHICS^R were tested for normality, log transformed to normalise the data, and tested for significant differences between sites or seasons using one-way ANOVA or the Kruskal-Wallis test (if the variances were not equal). Seasonal trends are illustrated by means of stacked bar graphs showing the monthly density of the dominant species and the maximum height of the bar represents the total density of invertebrates per month per site. Linear regression analysis was performed on the log transformed data in order to determine the relationship between drift density and benthos density (Paper VI, this thesis).

RESULTS

Macroinvertebrate drift density and biomass

A total of 36 taxa was recorded in the drift samples but only 10 showed a median value greater than zero at any site (i.e 26 taxa can be termed rare and are represented with a "+" in Table 1). Three out of the 10 viz. Trichoptera, Nematoda and Hydracarina, only had median values greater than zero at very few sites (respectively, PR8; PR2; and PR1 & 8: Table 1). The 7 dominant taxa comprised 4 benthic groups, Ephemeroptera, Chironomidae, Simuliidae and Oligochaeta, and three zooplankton taxa, Cladocera, Copepoda and Chaoboridae.

The total number of organisms collected in the drift samples at each site every month is listed in Appendix A. These values are not quantitative as they are the actual counts of organisms, and not numbers per volume of water sampled. These values indicate the extremely small numbers of macroinvertebrates found in the drift samples. The high numbers, particularly at sites PR3, PR7 and PR9, reflect the large quantities of lake-derived zooplankton in the outflow from the impoundments.

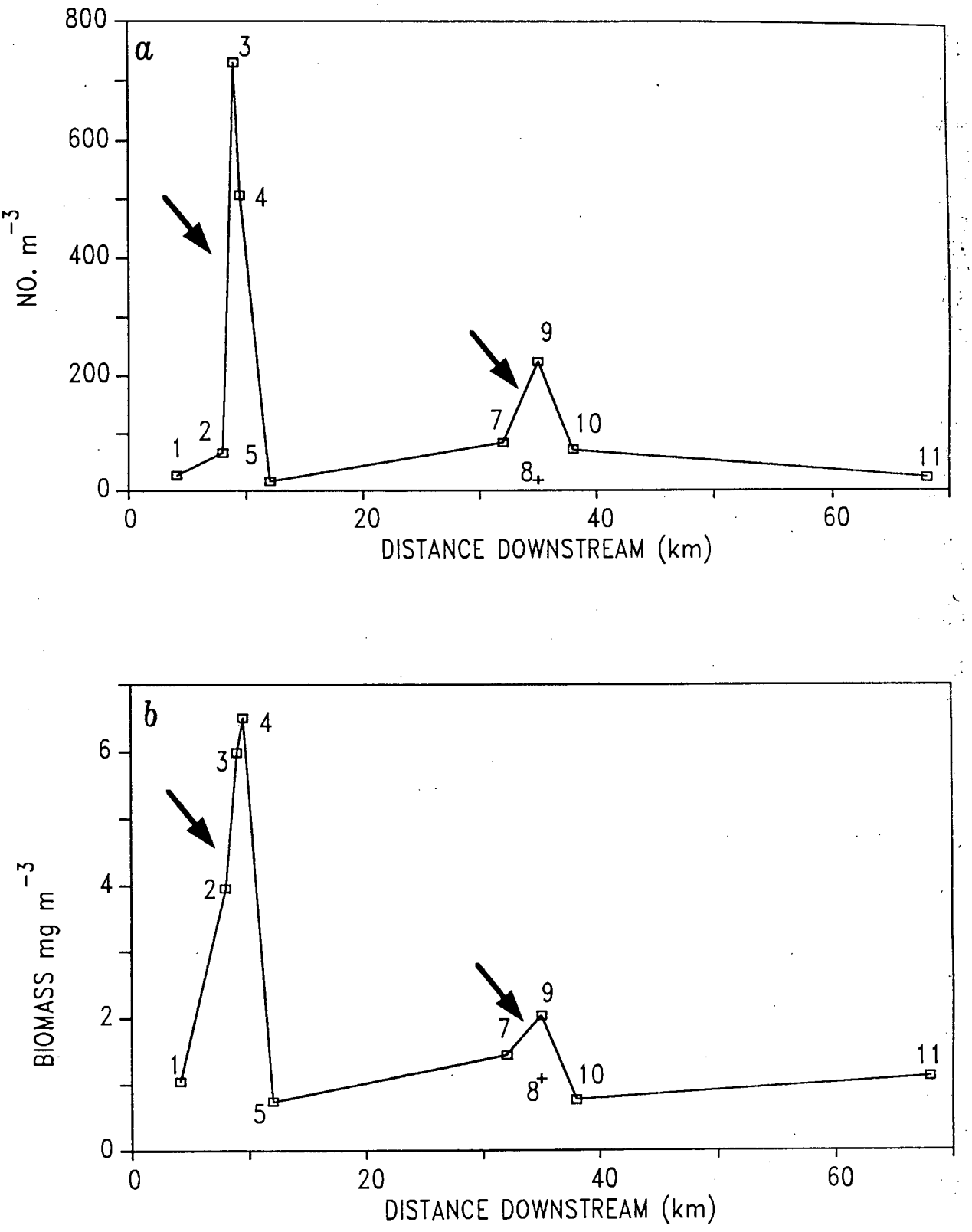

Figure 2: Graph showing the downstream changes in a) median drift density (no. m^{-3}) and b) median drift biomass (mg m^{-3}) for all taxa combined. The numbers inside the graphs refer to the site numbers and the arrows indicate the positions of the dams.

Table 1: Median density (no. individuals 100 m^{-3}) recorded for each taxon at each site (+ = taxon present but median value = 0: i.e. rare)

	PR1	PR2	PR3	PR4	PR5	PR7	PR9	PR10	PR11	PR8
Plecoptera	+	+	+		+	+		+	+	+
Ephemeroptera	148	244	+	+	40	58		+	124	58
Trichoptera	+	+	+	+	+	+			+	9
Simuliidae	67	136	+	+	+	66	84	+	235	42
Chironomidae	659	2587	559	4560	597	798	411	684	593	857
Ceratopogonidae	+	+	+	+	+	+			+	+
Chaoboridae	+	+	4134	46	+	+	431		+	+
Empididae		+								+
Rhagionidae	+	+	+					+	+	
Tabanidae	+									
Ephydridae	+									
Oligochaeta	98	614	33	63	41	13	321	+	83	27
Nematoda	+	88	+	+	+	8	+	+	+	+
Tricladida	+					+	+	+		+
Micronecta sp		+	+	+	+	+	+	+	+	+
Gerridae										+
Hydraenidae	+	+	+		+				+	+
Helodidae	+			+	+	+			+	+
Elmidae spA	+	+		+	+				+	+
Elmidae spB										+
Elmidae spC	14	+		+	+	+	+	+	+	+
Dryopidae		+								
Dytiscidae		+								
Coleoptera adults	+	+			+			+	+	+
Anisoptera	+	+				+		+	+	+
Lepidoptera		+		+	+				+	+
Megaloptera					+	+		+		
Copepoda	+	64	12380	13743	152	3049	4946	182	150	291
Cladocera	+	159	17794	4827	274	2170	3781	489	305	289
Ostracoda						+	+	+	+	+
Amphipoda	+	+								+
Hydracarina	17	+	+	+	+	+	+	+	+	136
Collembola	+	+	+		+	+	+		+	+
Mollusca						+	+	+		
Rotifera	+									
Hydra sp		+	+	+	+	+	+	+		+
TOTAL	25	26	17	17	22	22	15	19	23	28

Over the whole study, total median drift density (Figure 2a) increased from 66 individuals m^{-3} above Nuweberg (PR2) to 550 m^{-3} below the impoundment (PR3), decreased to 505 m^{-3} within 0.5 km (PR4) and then decreased markedly to 16 m^{-3} (PR5), well below the source value of 27 m^{-3} (PR1), over the next 2.5 km. Median drift biomass over the entire study (Figure 2b) also increased from above (PR2) to below (PR3) Nuweberg (4 to 6 mg m^{-3}) but then increased further to 6.4 mg m^{-3} within 0.5 km downstream (PR4) decreasing to 0.74 mg m^{-3} within the following 2.5 km (PR5). At Arieskraal median drift density (Figure 2a) increased from 83 individuals m^{-3} above the impoundment (PR7) to 224 m^{-3} below the impoundment (PR9), decreased to 71 m^{-3}

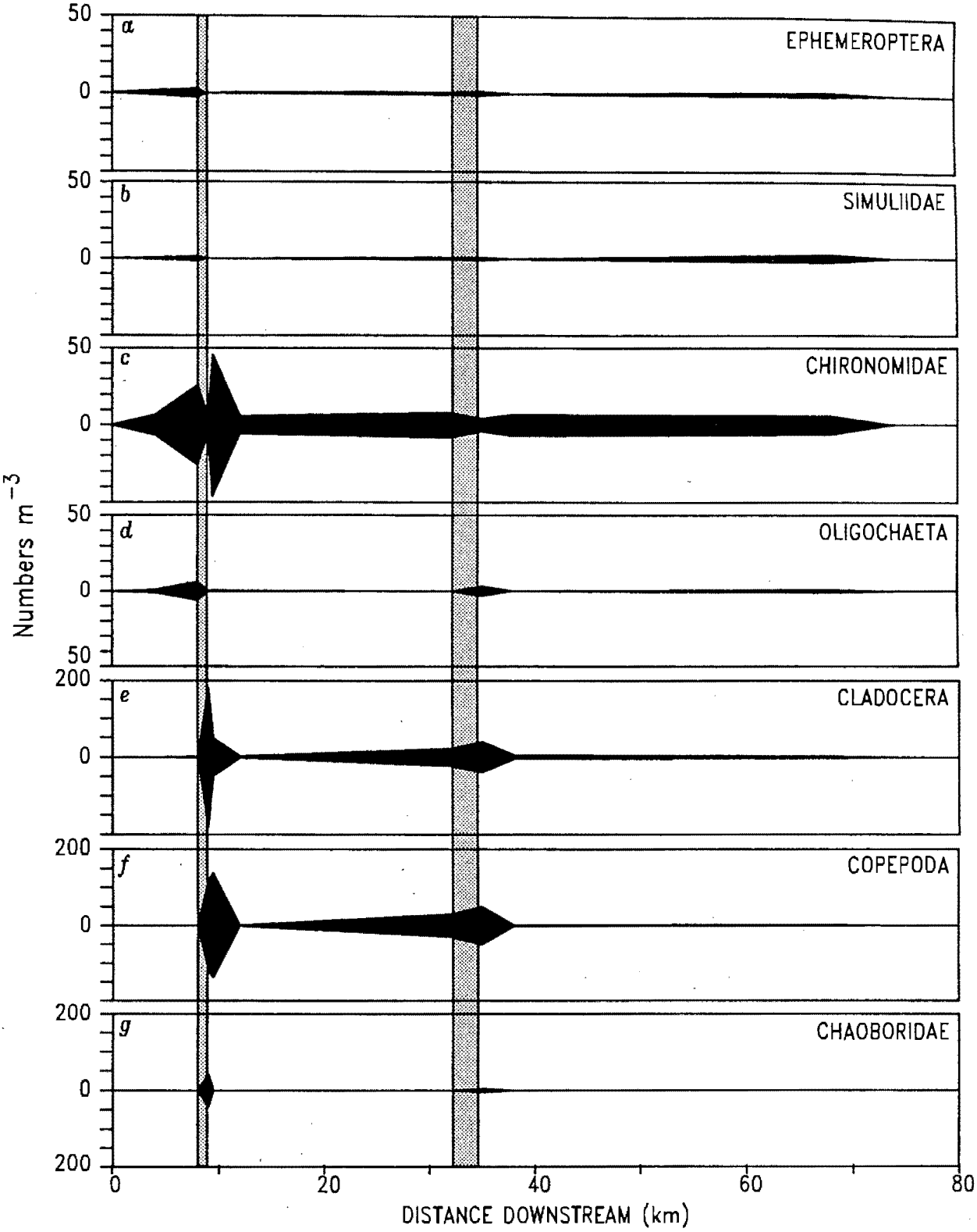

Figure 3: A composite figure showing the downstream changes in density of the seven predominant drift taxa and the effect of the dams (vertical spotted lines) on those densities. Note the scales differ for the benthic taxa (Ephemeroptera, Simuliidae, Chironomidae and Oligochaeta: scale = 0 to 50) and the zooplanktonic taxa (Cladocera, Copepoda and Chaoboridae: scale = 0 to 200).

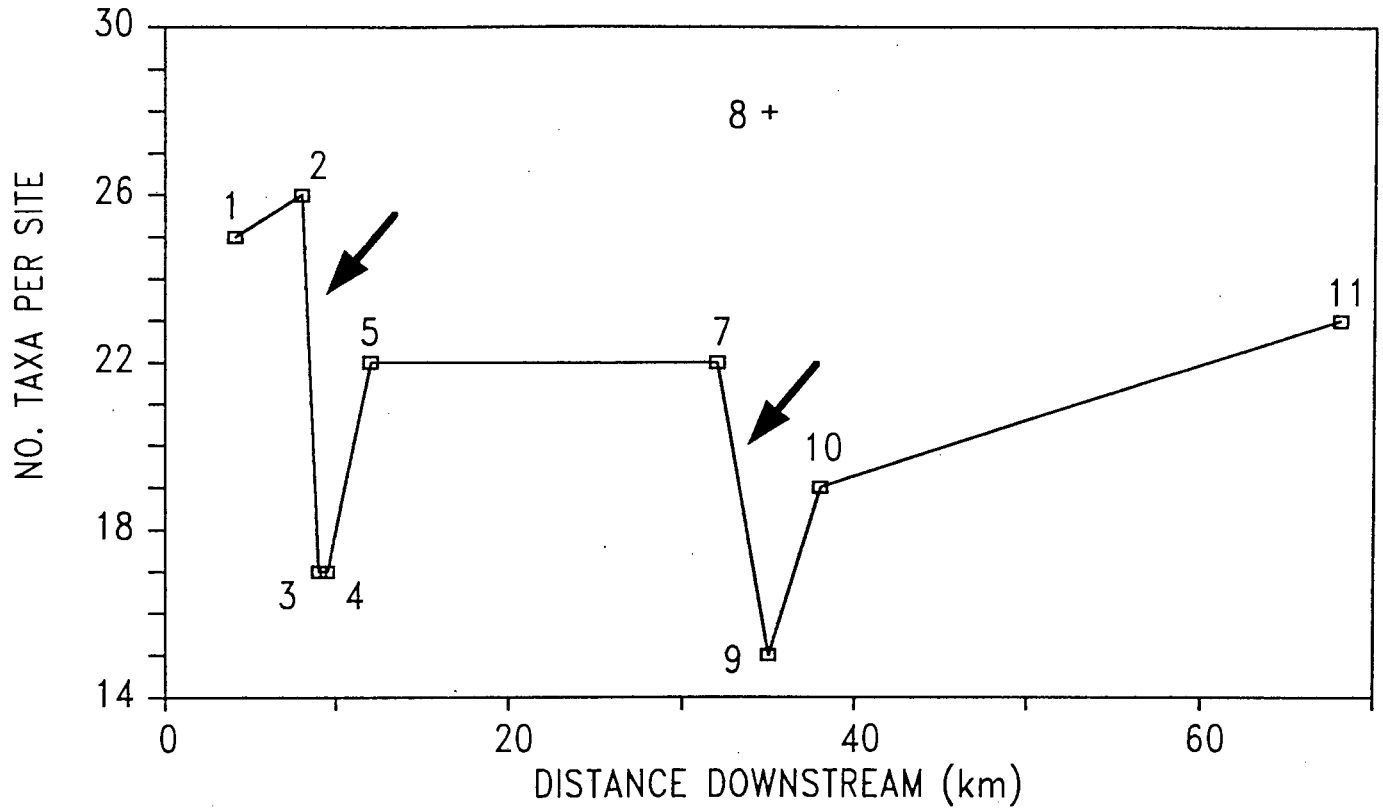

Figure 4: Downstream changes in drift taxonomic richness. The numbers inside the graph refer to the site numbers and the arrows indicate the positions of the dams.

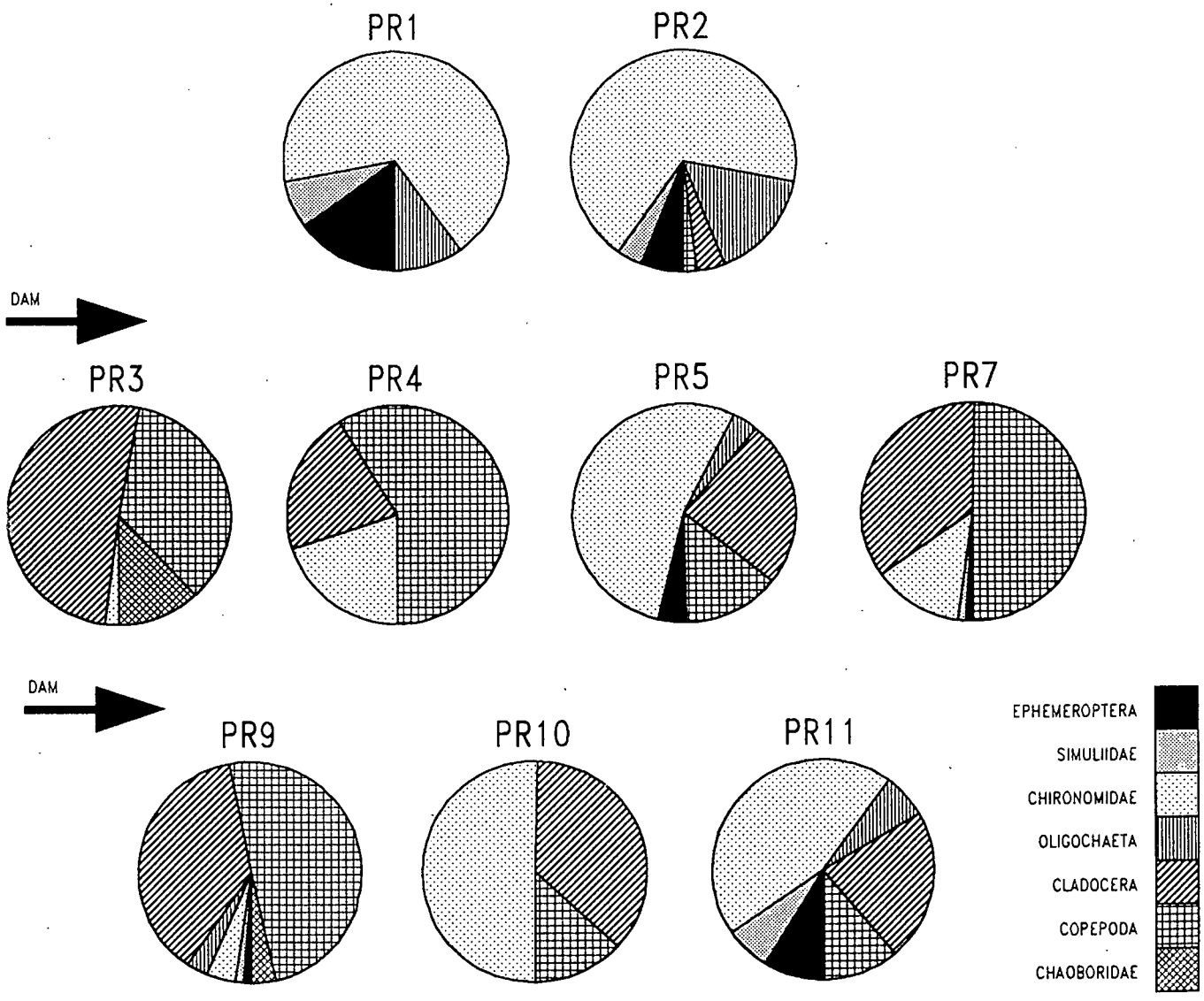

Figure 5: Drift species composition at each site. The arrows indicate the positions of the dams. PR# = site number.

within 3 km (PR10) and decreased still further to 23 m^{-3} at site PR11, just above the estuary. There was also an increase in median drift biomass (Figure 2b) from 1.44 mg m^{-3} above (PR7) to 2.02 mg m^{-3} below (PR9) Arieskraal, a decrease to 0.77 mg m^{-3} over the next 3 km (PR10) and an increase to 1.12 mg m^{-3} above the estuary (PR11).

The median densities of the different taxa of drifting zoobenthos (Figure 3a,b,c,d) decreased below Nuweberg and increased below Arieskraal, except for the Chironomidae (Figure 3c) which also decreased below Arieskraal. Below Nuweberg (PR3) the densities of Ephemeroptera (Figure 3a), Simuliidae (Figure 3b) and Oligochaeta (Figure 3b) did not return to the above-impoundment values within the 5 km before the next impoundment, Eikenhof. Ephemeroptera do occur, in very low numbers, in the benthos below Nuweberg but Simuliidae and Oligochaeta do not (Paper VI, this thesis). The densities of Chironomidae, although decreasing immediately below Nuweberg (Figure 3c), increased markedly at site PR4, 0.5 km below the impoundment and then decreased to values approximately equivalent to those near the source of the river (PR1) within the next 2.5 km (PR5) (Figure 3c). The densities of each zoobenthic taxon (excluding the Chironomidae) increased immediately below Arieskraal but then rapidly decreased to around zero within the next 3 km (Figure 3a,b,d) although Ephemeroptera and Simuliidae were present in the benthos at this site (PR10: Paper VI, this thesis). The density of Chironomidae (Figure 3c) decreased below Arieskraal but recovered within 3 km.

Table 2: Effect of impoundments on the variables measured and the distance within which recovery occurs.

Variable	Nuweberg		Arieskraal	
	effect	recovery distance	effect	recovery distance
Median drift density	incr.	3km	incr.	3km
Median drift biomass	incr.	3km	incr.	3km
Densities of individual taxa:				
Ephemeroptera	decr.	3km partial	incr.	none
Simuliidae	decr.	none	incr.	none
Oligochaeta	decr.	none	incr.	3km
Chironomidae	decr.	3km	decr.	3km
Cladocera	incr.	3km	incr.	3km
Copepoda	incr.	3km	incr.	3km
Chaoboridae	incr.	3km	incr.	3km
Taxonomic richness	decr.	3km; partial	decr.	30km

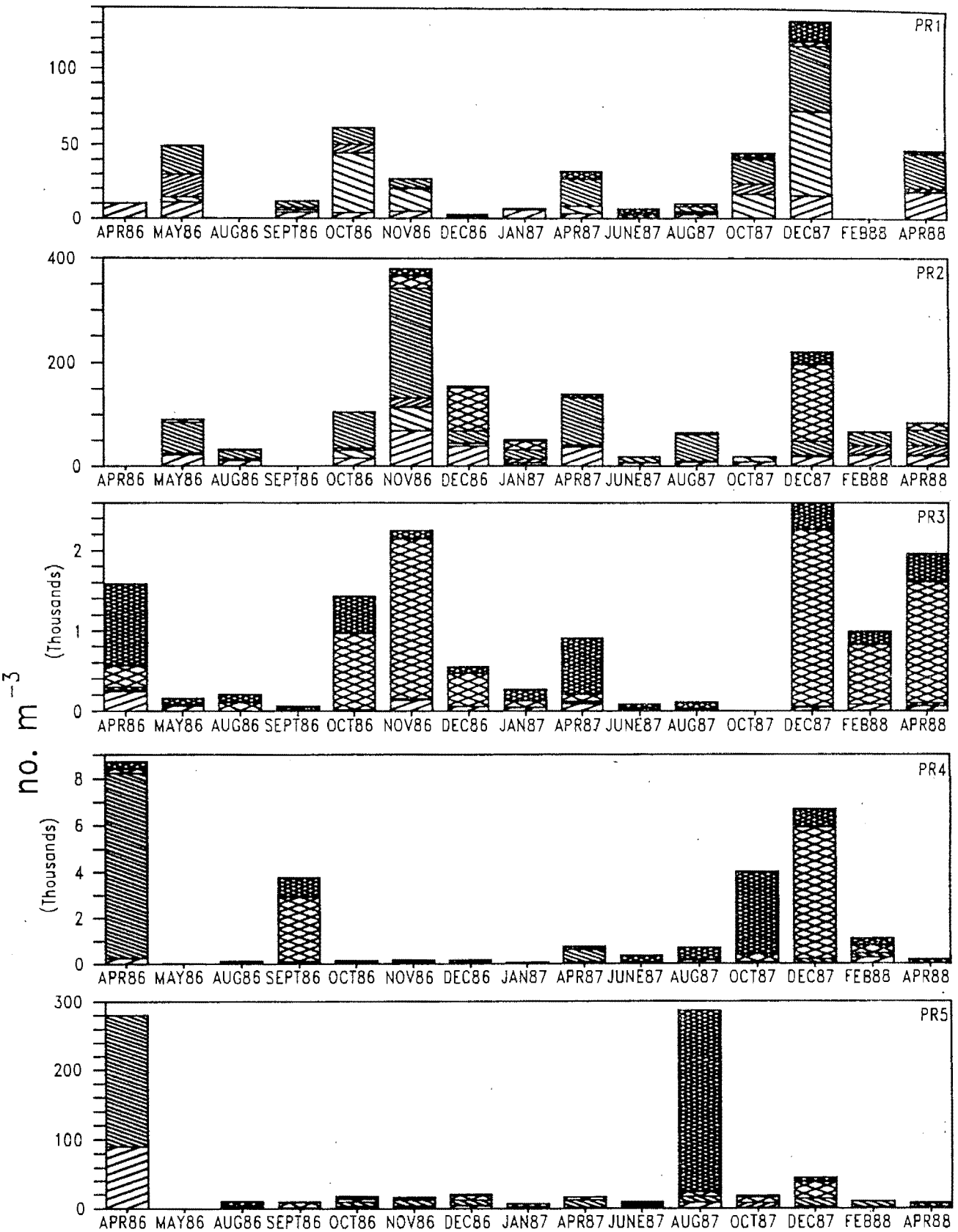

Figure 6: (see next page for legend)

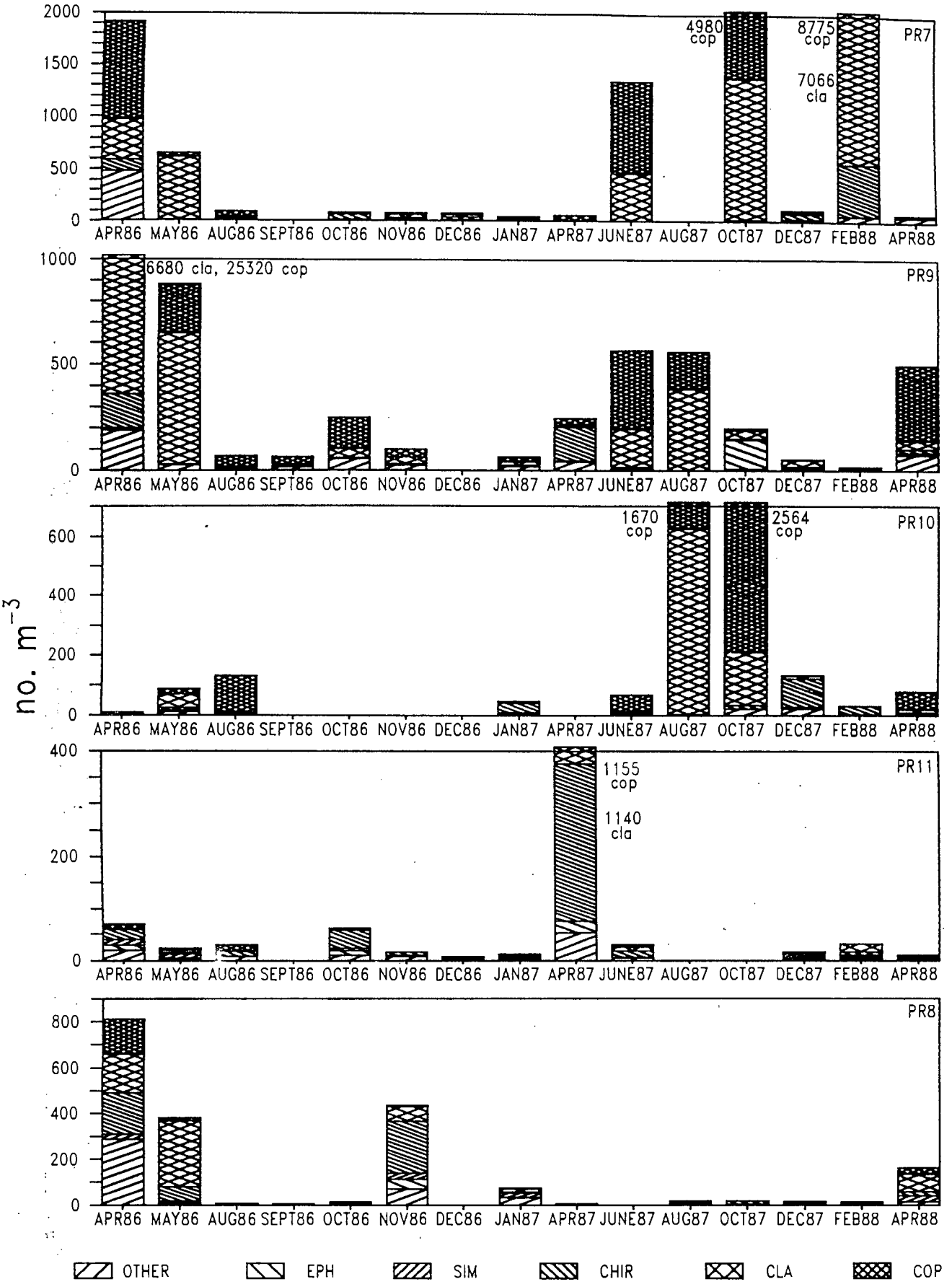

Figure 6: Stacked bar graphs of the density of each taxon for each sampling month at each site. The total height of each bar gives the total drift density for that sampling period. PR# = site number. EPH = Ephemeroptera; SIM = Simuliidae; CHIR = Chironomidae; CLA = Cladocera; COP = Copepoda; OTHER = all other organisms found in the drift.

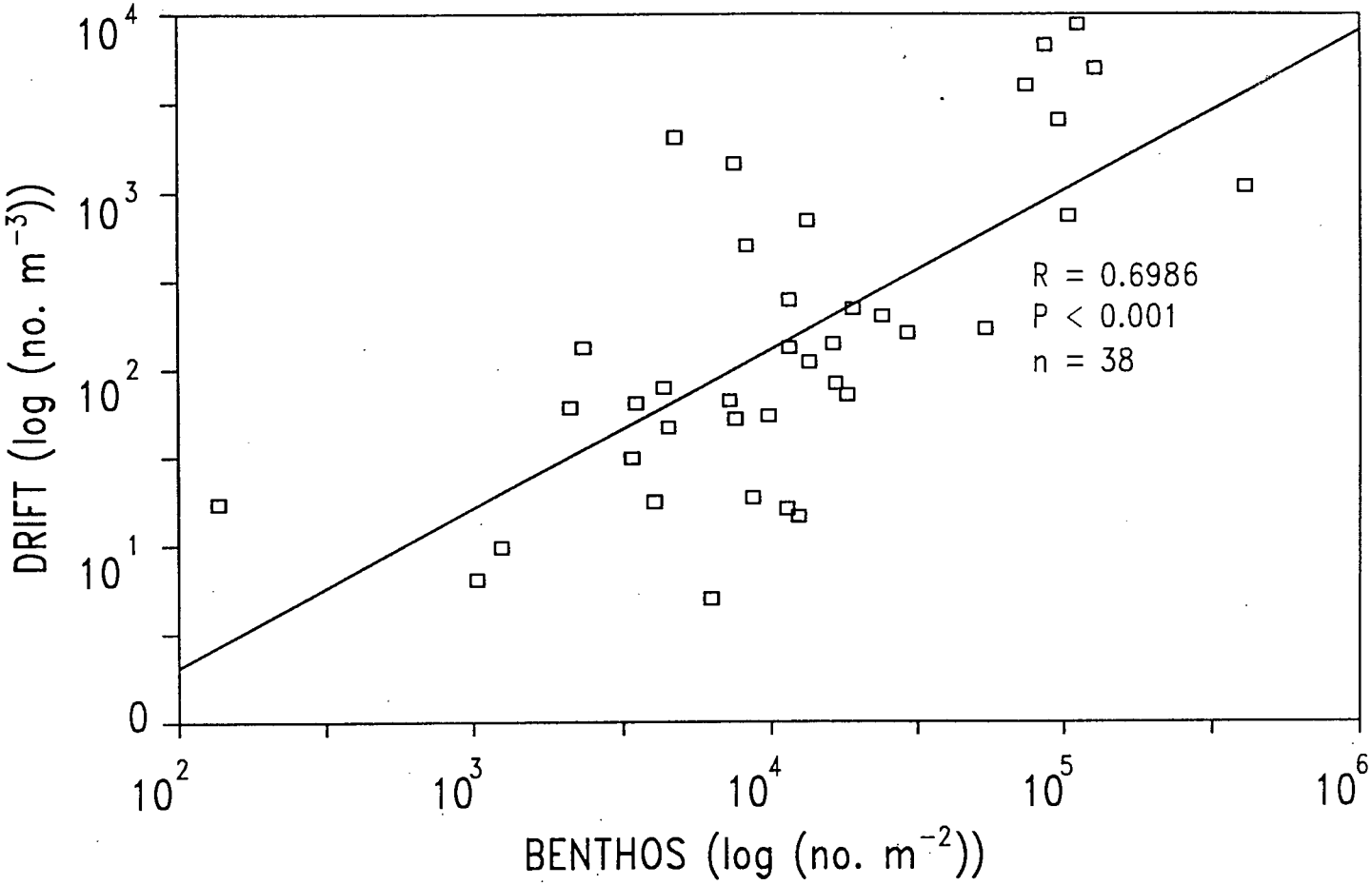

Figure 7: The regression line and points scatter for the log - log relationship between drift density and benthic density.

The numbers of drifting zooplankton, on the other hand (Figure 3e,f,g), increased markedly directly below both impoundments. Recovery occurred within 3 km for all zooplankton below both impoundments except for Chaoboridae below Nuweberg, where recovery was extremely rapid i.e. 0.5 km. Drift taxonomic richness, the total number of taxa found in the drift at each site, (Figure 4) decreased below both impoundments and did not recover fully within the 30 km above the estuary (Table 2).

Macroinvertebrate drift species composition

Analysis of the drift species composition at each site (Figure 5) showed that at site 1 the dominant organisms in the drift were all of benthic origin, and were predominantly of benthic origin at sites 2, 5 and 11. At the sites immediately below the impoundments (PR3 & PR9) and a short distance downstream (PR4 & PR10), as well as at the inflow to Arieskraal (PR7), the drift was dominated by organisms of lentic origin.

Statistical analysis

Statistical analysis (ANOVA or Kruskal-Wallis) of the densities, individuals m^{-3}, of the dominant taxa in the drift for each site and each season showed significant differences in numbers of individuals m^{-3} ($P<0.05$) between sites for all taxa except the number of oligochaetes, and very few significant differences (for ephemeropterans and chironomids only) between seasons (Table 3).

Table 3: Significance levels (** = $p<0.01$ and * = $p<0.05$) for ANOVA analysis of drift macroinvertebrates for site or season. For site analysis n = 130 and for seasons n = 136.

SAMPLE	SITE/ SEASON	ANOVA	VARIANCE	KRUSKAL-WALLIS
Ephemeroptera	SITE	**	=	
	SEASON	*	=	
Simuliidae	SITE	**	=	
	SEASON	ns	=	
Chironomidae	SITE		≠	**
	SEASON		≠	**
Oligochaeta	SITE	ns	=	
	SEASON	ns	=	
Cladocera	SITE	**	=	
	SEASON	ns	=	
Copepoda	SITE		≠	**
	SEASON	ns	=	
Chaoboridae	SITE		≠	**
	SEASON		≠	ns

Seasonality

Figure 6 shows a stacked bar graph of the number of individuals m^{-3} per taxon per site per month sampled. The total height of the bar gives the total number per site per month and where the bar exceeds the scale the excesses comprised Copepoda or Copepoda and Cladocera. In the upper reaches above the impoundment and immediately below Nuweberg maxima appear to occur in spring/summer (October to December) as well as in April (autumn). In the middle to lower reaches maxima vary between sites but rarely occur in summer, with peaks in August and April occurring quite frequently.

Relationship between drift density and benthic density

Regression analysis on log transformed data of drift and benthic density (Paper IV, this thesis) per site per month showed a highly significant relationship, $r = 0.6986$, $p<0.001$, $n=38$ (Figure 7). If analysed by site only two sites, PR2 (inflow to Nuweberg: $n=7$) and PR8 (tributary: $n=5$) showed significant relationships ($p<0.05$).

DISCUSSION

General trends in macroinvertebrate drift density and diversity

The density of the dominant benthic taxa in the drift at the sites unaffected by impoundments (PR1, PR2, PR8 & PR11) was around 10 organism m^{-3} with a biomass of around 1 mg m^{-3} which compares well with other figures given in the literature. Benke *et al.* (1986) working on a blackwater subtropical river, the Satilla River, Georgia, US, recorded densities of 2 - 5 m^{-3} with biomass of 0.2 - 0.5 mg m^{-3}, approximately half of the values recorded in the present study. However, Benke *et al.* (1991), in an unregulated coastal plain river, Ogeechee River, US, found densities of 20.4 - 22.8 m^{-3} and biomass of 2.41 - 2.46 mg m^{-3} (more than double the quantities found in the undisturbed sites in the Palmiet River) and commented that these values were some of the highest ever recorded for benthic invertebrate drift (Benke *et al.*, 1991).

Three of the four benthic taxa that predominate in the drift, viz. Ephemeroptera, Chironomidae and Simuliidae, have been found to be important taxa in the drift in many other studies. Simuliidae have been shown to be a major component of the drift in lotic

systems (Hynes, 1970; Waters, 1972) including in the Vaal River in South Africa (De Moor *et al.*, 1986). Williams (1989) found that chironomid larvae predominated in the drift of the River Chew in south-western England. Both Neveu (1974) and Scullion and Scinton (1983) found Chironomidae constituted an important fraction of the drift. Brittain and Eikeland (1988) commented that in swift flowing temperate streams, the insect taxa Ephemeroptera, Simuliidae, Plecoptera and Trichoptera are usually of most quantitative importance. Plecoptera were recorded in the drift, but classed as "rare", at 8 of the 10 sites sampled on the Palmiet River. Trichoptera, although present in the benthos at most sites (Paper IV, this thesis), were found, but "rare", in the drift at all sites except the two sites below Arieskraal (PR9 & 10) where they were absent. Waringer (1989) showed that caddis larva engage in active resistance to drift as a result of the effective larval attachment to the substratum and this may be a reason for the low numbers of Trichoptera found in the drift in the Palmiet River.

Of interest, in the Palmiet River, are the fairly large densities of oligochaetes (mainly lumbricids: B. A. Gale, pers. obs.), compared with the densities of other taxa found in the drift, especially at sites 2 & 9 where they form 17% and 35%, respectively, of the benthic invertebrates in the drift. Oligochaeta, not mentioned at all in the drift literature, do not have an aerial phase to complete a colonisation cycle (*sensu* Müller, 1954) and do not occur in large numbers in the benthos of the Palmiet River (except at site 2; Paper IV, this thesis which seems to indicate that their appearance in the drift is probably due to catastrophic dislodgement. Analysis of the seasonal trends in the appearance of Oligochaeta in the drift shows that they are probably dislodged from the substratum during flooding. Oligochaeta occur in large numbers during April (the month of the first winter rains) and in other samples taken during or soon after heavy rain (i.e. on the rising limb of the hydrograph). Factors such as sudden changes in light, temperature and water flow (discharge and/or velocity) have all been shown to cause an increase in the number of animals entering the drift (Minshall and Winger, 1968; Tarshis and Neil, 1970; Waters, 1972; Gore, 1978). An increase in animal drift could also be due to dislodgement caused by movement of predators and other animals in the area of benthic colonisation (Hall and Edwards, 1978).

The RCC (Vannote *et al.*, 1980) predicts maximum biotic diversity, a part of which is assumed to be drift diversity (interpreted here as taxonomic richness), in the middle reaches of a river, whereas in the Palmiet River maximum drift taxonomic richness, occurs in the headwaters (PR1) and in the pristine tributary (PR8). The RCC also predicts that plankton levels will be low in the upper and middle reaches and increase steadily towards the mouth. In the Palmiet River zooplankton levels are very low throughout except immediately below the impoundments. Although the RCC is based on 11^{th} order streams with forested headwaters it is said to be globally applicable. The longest river in South Africa, the Orange River, is only a 7^{th} order stream and most other rivers in South Africa only reach 5^{th} or 4^{th} order or less. The RCC assumes a wide, slow flowing lower reach, whereas the lower reaches of the Palmiet River are fairly narrow and consist of alternating sections of pools and riffles as the river passes through the unperturbed coastal mountains of a Nature Reserve to the estuary - an uncommon occurrence in South Africa and in other parts of the world. The lower reaches of the Palmiet River can thus be said to be atypical and since the species composition of the drift is similar in the upper and lower sections of the river, the river could be said to consist of upper - middle - upper reaches with no typical lower reach/ flood plain zone.

Effect of impoundments on drift composition, density and diversity

Impoundments alter the composition of stream invertebrate drift as they introduce large numbers of lentic organisms into the system. However, these organisms, which are not adapted to lotic environments, often settle out within a very short distance below the impoundment. A number of workers have studied the successive downstream decline in the amount of limnoplankton in lake outlet streams (Chandler, 1937: Reif, 1939; Maciolek and Tunzi, 1968; Ulfstrand, 1968) and have often concluded that they provide a valuable food source for other organisms, particularly fish. In the Palmiet river, median density and biomass of drifting organisms increased markedly below both impoundments and comprised mainly limnoplankton. The density and biomass then decreased rapidly within 3 km to levels close to or below the densities and biomass found in the sites above the impoundments. In the Palmiet river there are only three species of indigenous fish (*Galaxias zebratus*, *Sandelia capensis* and *Anguilla mossambica*) which occur in very low

numbers (CDNEC, 1984). Thus the limnoplankton probably settles out onto the river bed and adds to the detrital food chain.

According to the literature, deep-release impoundments do not transport large amounts of limnetic plankton (Ward, 1976) compared with lakes and surface-release impoundments (Voshell and Parker, 1985). However, from Table 4 it can be seen that Nuweberg, an entirely bottom-release structure (the spill-way only enters the river below site PR3), showed an increase in copepods and cladocerans which was proportionally higher (i.e. percent increase, Table 4) than two of the surface release impoundments on the Buffalo River, Rooikrans and Laing (Palmer and O'Keeffe, 1990).

Table 4: A comparison of the increase in the maximum number m^{-3} of copepods plus cladocera below the impoundments on the Palmiet River with the impoundments on the Buffalo river (Palmer and O'Keeffe, 1990). The percentage increase = below/above x 100. Surface release depth means that release only occurs when there is overspill; bottom release means that no spilling enters above that site; bot/surf = bottom release with surface over-spill during the rainy season.

	PALMIET			BUFFALO		
	Nuweberg	Arieskraal	Maden	Rooikrans	Laing	BridleDrift
			max. no. m^{-3}			
above	171	10095	52	67100	30400	5200
below	3225	24960	18340	68022	188900	100900
percent increase	1886%	247%	35269%	57%	621%	1940%
release depth	bottom	bot/surf	surface	surface	surface	bot/surf

The bottom/surface release impoundment on the Palmiet River, Arieskraal, showed an increase in copepods and cladocerans below the impoundment that was proportionally (percent increase, Table 4) much less than the increase below the bottom/surface release impoundment on the Buffalo River (Bridle Drift, B3: Palmer and O'Keeffe, 1990). These data indicate that downstream release of limnoplankton is not related solely to release depth. Other factors such as, for example, the total depth of the lake and vertical migration of certain zooplankton species, need to be taken into account.

Several other factors might regulate the quantity of limnoplankton released downstream of an impoundment. These include life cycle characteristics (O'Hop and Wallace, 1983) and seasonal changes in the density of limnoplankton as well as diel migration patterns and

climatic conditions. The very high median numbers of copepods and cladocerans recorded in the drift below Nuweberg might reflect the spring/summer reproduction phase as well as migration away from the hot, bright surface during the day, resulting in capture by the deep-release outlet pipe. Below Arieskraal, a deeper impoundment with bottom release during summer and overtopping during the rainy season, the increases in limnoplankton are related to the rising limb of the hydrograph (i.e the beginning of heavy rains).

The SDC (Ward and Stanford, 1983) predicts that both upper and middle reach impoundments will result in a decrease in biotic diversity (defined here as taxonomic richness) in the receiving stream, with a much shorter recovery distance below the upper-reach impoundment. In the Palmiet River both impoundments caused a decrease in drift taxonomic richness. However, below the upper-reach impoundment only partial recovery occurred before the river entered the next impoundment approximately 7 km downstream, whereas below the middle-reach impoundment partial recovery occurred within 3 km and full recovery before the river entered the estuary, approximately 30 km downstream (Table 2). The SDC also predicts that the plankton addition to the stream would be greater below the middle-reach as opposed to the upper-reach impoundment and that recovery below both impoundments would be rapid. However, the upper-reach impoundment on the Palmiet River introduced far larger numbers of zooplanktonic organisms into the river than the middle-reach impoundment did (median numbers: Table 1), although recovery below both was very rapid (3 km: Table 2). This reversal in plankton response may be due to the differing release mechanisms of the two dams, as mentioned above.

Contrary to the effect of most impoundments, which result in a settling out of sediment particles and the release of clearer water downstream, the impoundments on the clear Palmiet River result in an increase in the quantities of suspended particulate matter directly below the impoundments - particularly the ultra-fine matter (Paper II, this thesis). Rosenberg and Wiens (1975) showed that experimental sediment addition in the Harris River in north-western Canada clearly increased the numbers of macroinvertebrates drifting. Results from comparative and experimental studies on the effect of sediment addition on biotic processes indicate that, as quantities of fine sediment increase, macroinvertebrate drift rates increase and, consequently, the density and species diversity of the benthic

macroinvertebrate community is reduced. Culp *et al.* (1986) set out to test this and found that sediment deposition had no measurable impact on most taxa except on an ephemeropteran *Paraleptophlebia* sp, which showed significantly higher drift rates and lower benthic densities at increased silt concentrations. Culp *et al.* (1986) concluded that catastrophic drift was initiated by fine sediments that slid and bounced along the surface of the stony substrate and that sediment saltation has the potential to act as a community level disturbance early in the storm hydrograph or at lower discharge magnitudes than required to suspend sediments. The increase in fine sediment below the impoundments on the Palmiet River could contribute to the increase in drift, especially below Nuweberg where the chironomid larvae component of the drift increases from the site directly below the impoundment (PR3) to the site 0.5 km away (PR4).

Seasonal trends

Although much work has been done on seasonal and diel trends in stream invertebrate drift little consensus has been reached, which implies that overall generalisations cannot be made and that often changes are situation specific. Many workers have found strong diel variation in drift patterns of benthic macroinvertebrates, related to light intensity, with greatest abundance occurring at night (Waters, 1962; Elliott and Minshall, 1968; Brooker and Hemsworth, 1978; Allan, 1985), often immediately after sunset (Adler *et al.*, 1983), with nights of strong moonlight causing a decrease in abundance (Hynes 1975). O'Hop and Wallace (1983) showed that the numbers and biomass of drifting organisms reflected the seasonal cycles of aquatic insects. However, Allan *et al.* (1988) working in the Dan River, Israel, assessed diel, seasonal and spatial patterns of the abundance of drifting invertebrates. They showed that diel and seasonal periodicity in drift was detectable, but minimal, with dipteran larvae showing no diel variation and the authors suggested that this was probably attributable to the extremely constant physical regime within the rivers. Ferrington (1984), studying the drift patterns of chironomids in two North American streams, found three species or species groups with nocturnal peaks in Linesville Creek, Crawford County, north-western Pennsylvania, USA, and four species with diurnal drift peaks in 'Inlet Run', Beartooth Plateau, Wyoming-Montana border, USA. Ferrington (1984) concluded that random factors greatly influence the apparent diel drift pattern of Chironomidae. Since the sampling on the Palmiet river was undertaken at approximately the same time each month at

specific stations (i.e the sites were sampled in the same order each month) the results, although not providing diel data, are directly comparable and give a good indication of monthly/seasonal trends.

Relationship between discharge and/or flow rate and macroinvertebrate drift density

Drift of stream organisms has often been correlated with discharge and numbers of invertebrates in the drift may increase with both increasing and decreasing discharges (review by Waters, 1972; Brooker and Hemsworth, 1978; Scullion and Scinton, 1983). The relationship between drift and discharge is poorly understood and many different results have been obtained. Perry and Perry (1986) commented that the magnitude of response of invertebrates to disturbance was different in two study rivers, in part because of different frequencies of flow changes. Perry and Perry (1986) also found that the length of time high river discharges were maintained prior to flow reductions was an important factor governing the magnitude of the drift response. Allan *et al.* (1988) found that a 50% reduction in flow rate had no discernible effect on drift. Hynes (1975) found that high numbers in the drift were inversely correlated with the rate of flow, whereas low drift numbers showed no correlation with flow. Hynes (1975) briefly reviewed studies where increased flow rates resulted in high numbers in the drift while at low rates the numbers decreased, as well as studies which observed the opposite, namely low drift with high flow rate and *vice versa*. Ciborowski *et al.* (1977) suggested that changes in current velocity are more important in determining the magnitude of drift than is the absolute current velocity (see also Pearson and Franklin, 1968). Brooker and Hemsworth (1978) summed up the situation well by concluding that rapid changes in flow resulting from natural or artificial causes substantially modify the drift of invertebrates in rivers. In the Palmiet River no correlation between drift numbers and discharge was found. The month in which the highest densities of drift occurred did however correspond, in many cases, with an increase in discharge.

Drift density vs benthic density

One would expect the density of stream benthos, especially that associated with stones, to vary with the density of organisms in the drift. Graesser and Lake (1984), working on the Toorongo River, Australia, found that five of the 10 most common taxa displayed a general trend of reaching day-time peaks in the benthos and night-time peaks in the drift. The total

benthic density reached a significant peak in the day-time while total drift density peaked at night. If benthic macroinvertebrates are dislodged passively from the stones at night, as suggested by Elliott (1967a,b), or enter the water column actively in response to levels of immediately available resources such as food (Waters, 1966, 1972; Hildebrand, 1974), then one could reasonably expect a nocturnal decline in benthic density and a simultaneous increase in drift density. Such appears to be the case in the study by Graesser and Lake (1984). For other taxa the relationship between drift density and benthic density varies with sampling occasion probably as a result of vertical migrations within the substratum (hyporheos). In the Palmiet River there is a significant correlation between benthic density (Paper IV, this thesis) and drift density. This could also be the result of accidental drift as the higher the benthic density the more chance there is for 'accidents' to occur. Statzner *et al.* (1985) concluded that ".... a net of behavioural interactions in the benthic population had a large effect on the loss of individuals through drift".

CONCLUSION

There are a multitude of factors which appear to cause benthic organisms to enter the water column as stream drift. There are many more factors which affect the density of organisms in the drift. Impoundments introduce 'artificial' alterations to stream drift and their effect is dependent on the reservoir size, release mechanism, surrounding water requirements and the length of unperturbed river reach below the impoundment over which recovery can occur. The general trends of invertebrate drift in the undisturbed portions of the Palmiet River do not correspond to the biotic diversity (interpreted here as drift taxonomic richness) and plankton predictions of the RCC, and the effects of an upper and middle reach impoundment differ from those predicted by the SDC. Owing to the limitations placed on drift collection by the magnitude of the sampling programme, and since both the mechanism and reason for drifting of benthic invertebrates is still not fully understood, generalisations on the effect of impoundments on macroinvertebrate drift patterns are difficult to make. It appears that changes in drift patterns engendered by upstream impoundment may be situation specific and that different types of impoundments may have varied influences.

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Appendix A: The total number of organisms collected in the drift samples at each site every month is listed in Appendix A. These values are not quantitative as they are the actual counts of organisms, and not numbers per volume of water sampled.

month/ site	4/86	5/86	8/86	9/86	10/86	11/86	12/86	1/87	4/87	6/87	8/87	10/87	12/87	2/88	4/88
PR1	1	289	59	48	240	105	5	6	100	12	67	81	396	3	203
PR2	0	529	311	0	125	1813	699	164	456	84	324	2	1468	118	420
PR3	158	983	1076	279	6560	12945	3266	1870	4165	1368	717	573	18934	8067	7714
PR4	874	109	732	5974	1134	883	689	387	1840	3020	3177	17284	38068	237	1100
PR5	28	0	29	75	66	64	78	12	40	18	1953	46	153	45	16
PR7	191	5240	488	3305	777	464	408	286	432	6204	0	38366	191	44256	144
PR8	80	4364	46	33	59	3037	141	155	45	0	193	88	81	12	321
PR9	2532	8274	222	630	2431	370	671	256	637	2964	3315	495	73	37	1357
PR10	1	632	879	0	0	0	199	273	0	416	11247	12068	433	43	548
PR11	7	360	226	0	339	28	32	56	4448	183	2624	2	45	139	36

COMMUNITY STRUCTURE OF BENTHIC MACROINVERTEBRATES IN A REGULATED, MOUNTAIN STREAM.

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COMMUNITY STRUCTURE OF BENTHIC MACROINVERTEBRATES IN A REGULATED MOUNTAIN STREAM.

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ABSTRACT

Impoundments may severely alter benthic macroinvertebrate communities locally and downstream from the dam. This study was aimed at determining the applicability of the Serial Discontinuity Concept (SDC) to a South African mountain stream with respect to macroinvertebrate community structure. Benthic macroinvertebrates were collected bimonthly from February 1987 to April 1988, at six sites on the Palmiet River and one site on a tributary, using a modified box sampler. Variables are said to increase or decrease below impoundments with respect to their "above impoundment" values. A total of 79 macroinvertebrate taxa was recorded. Chironomid larvae had the highest density at each site with the highest median of 72 267 m^{-2} at a site 0.5 km below Nuweberg. This site also showed the highest total invertebrate density with a median of 61 240 individuals m^{-2} and a maximum of 459 200 m^{-2} . Of the 58 taxa analysed, 40 either increased or decreased in median number below one or both of the impoundments. The other 18 taxa were either absent or rare both above and below one or both impoundments. In all monthly samples species diversity (Shannon index) decreased below Nuweberg whereas below Arieskraal species diversity varied greatly over time. Taxonomic richness (the total number of taxa recorded at each site) was highest (48 taxa) at the site on the tributary, the Klein Palmiet. Benthic macroinvertebrate taxonomic richness decreased below both impoundments and did not recover within the three kilometre sampling stretch below Arieskraal. Chironomid larvae predominated at all sites except in the pristine headwaters, where ephemeropterans were dominant (45% by number). Chironomids increased from an above-impoundment value of 57% by number to 96% of the total population by number below Nuweberg. Below Arieskraal simuliids increased from 2% by number above the impoundment to 28% by number below, and the Chironomidae and Simuliidae comprised 77% of the total. Within three kilometres the Chironomidae again became dominant comprising 86% of the total. Trichopteran numbers were low at the pristine sites, increased markedly below Nuweberg, increased still further towards the middle reaches and then decreased below Arieskraal. In the middle reach sites the community was dominated by Hydropsychidae, predominantly *Cheumatopsyche* sp. Two-way indicator species analysis (TWINSPAN) showed two distinct groups: almost all the samples from the pristine headwaters and the pristine tributary, and all the samples from the sites below impoundments. The community composition of the benthic macroinvertebrates in the Palmiet River and their response to impoundment has highlighted some difficulties in predicting the biological impacts of impoundment.

INTRODUCTION

Impoundment may severely alter the structure and/or functioning of the benthic macroinvertebrate communities locally and downstream from the dam (eg. Munn and Brusven, 1991). The influence of impoundment on macroinvertebrate communities was discussed early in the 1960s and 1970s by Neel (1963) and Spence and Hynes (1971) and as recently as the 1990s by Munn and Brusven (1991). The physical, chemical and biological conditions created in the streams below reservoirs are usually much different from those before impoundment (Neel, 1963; Ward and Stanford, 1979; Armitage, 1984; Novotny, 1985). The relative immobility of most aquatic invertebrates renders them sensitive to impoundment effects (Weisberg *et al.*, 1990). Some organisms do not survive in tailwaters because they are unable to adapt to the habitat changes induced by upstream impoundment. Some species that occur in natural streams are eliminated or decrease in abundance, while others become abundant (Novotny, 1985).

Many of the studies on the environmental changes induced in streams by regulation and the effects of regulation on lotic macroinvertebrate communities, are extensively discussed in the comprehensive review by Armitage (1984). Armitage (1984) synthesised the available information on invertebrate responses to modified flow and temperature regimes, to changes in water quality and to the quality of suspended particulate matter downstream of reservoirs. Armitage (1984) noted that there was a preponderance of reviews and general monitoring studies and a relative lack of investigations into causal relationships and hypothesis-orientated studies. This problem still exists, despite a few new hypothesis-orientated studies (e.g. Munn and Brusven, 1991). These studies are important for a thorough understanding of the effects of regulation on stream biota and are essential if any attempt is to be made to generate predictive models (Armitage, 1984).

Historically, the interaction between environmental factors and riverine faunas was interpreted with respect to the theory that rivers are partitioned into discrete units from headwaters to mouth (Corkum, 1989). Thus, the River Continuum Concept (RCC: Vannote *et al.*, 1980) which predicts structural and functional changes in macroinvertebrate stream communities on a longitudinal and seasonal basis (Munn and Brusven, 1991) became a useful framework for lotic studies. However, due to the diverse nature of lotic ecosystems

the prediction of downstream changes in lotic invertebrate community structure, and the successful application of these predictions to other drainage basins in biomes that are different to the temperate, Northern Hemisphere streams on which the concept was based (Minshall *et al.*, 1985) and in other parts of the world (e.g. New Zealand: Winterbourn *et al.*, 1981), has been difficult (Corkum, 1989).

The serial discontinuity concept (SDC: Ward and Stanford, 1983a) is a conceptual model that predicts the type and degree of ecological change downstream from an impoundment (Munn and Brusven, 1991). This concept interprets an impoundment as a discontinuity in the river continuum and invokes a "discontinuity distance" that is dependent on the type of dam and its position along the river continuum, and predicts the 'resetting' of a variable to some upstream or downstream equivalent (Byren and Davies, 1989; O'Keeffe *et al.*, 1990; Munn and Brusven, 1991). Ideally, pre-impoundment data should be known before measurements of 'discontinuity' can be attempted but since no pre-impoundment data were available for this system I have preferred to use the term "recovery distance' as a better description of the processes which occur in the receiving reaches of rivers below dams. Therefore, in the present study, the definition of 'recovery distance' is *that length of stream which is required for any parameter to return to values close to those measured at the inflow to the impoundment or to achieve a new dynamic equilibrium* (Byren and Davies, 1989; O'Keeffe *et al.*, 1990).

In the SDC the only biological variable which relates to benthic macroinvertebrates is 'biotic diversity' and this is not defined i.e it could be interpreted as number of taxa or species (i.e. richness) or as some form of diversity index that incorporates richness and abundance. Studies on the effects of impoundments on the downstream biota have often compared the streams above and below very large reservoirs (e.g. Ward and Stanford, 1979). Results from these studies often conflict (Ward, 1976) as changes are not only related to the disruption caused by the impoundment but are also due to the vastly different positions in the river continuum between the upstream and downstream sites. By studying small impoundments, as was done in the present case, differences due to longitudinal gradients may be eliminated and the changes that occur could be attributed to the impoundment itself (Zeiser, 1985).

This study was aimed at determining the applicability of the SDC to a South African mountain stream with respect to macroinvertebrate community structure. Since the SDC only considers one impoundment in either the upper or the middle or the lower reaches of a river, this project was also aimed at determining the possible synergistic effect of multiple impoundment on benthic macroinvertebrate communities.

STUDY AREA

The Palmiet River, south-western Cape (Figure 1), described fully in Byren & Davies (1989), is a 74 km long cool, acid, blackwater, mountain stream which drains a catchment of approximately 500km^2, lying between latitudes 34°02'-34°21' and longitudes 18°53'-19°10' (Nel, 1980; Clarke, 1989) (Figure 1). The river rises in the vicinity of the Landdroskop (1133m AMSL), in the Hottentots Holland Mountain Range in the western Cape (Figure 1). The dominant vegetation comprises mountain fynbos, which typically consists of low, fire-adapted, sclerophyllous, indigenous shrubland with mostly no canopy over the river. The gradient of the Palmiet River is steep (Figure 1) and the river ranges between 3 and 20 m in width. The climate is mediterranean, with a strongly seasonal rainfall: most rain falls in the austral winter (May-September), flow rate varying from 0.02 to 1.0 m^3s^{-1} in summer and from 0.32 to >4.0 m^3s^{-1} in winter (Byren and Davies, 1989).

The underlying geology of the catchment is predominantly sandstones of the Table Mountain Series (TMS) in the upper and lower reaches resulting in a river substratum consisting mainly of pebbles, stones and boulders. The sandstone is interspersed with bands of Bokkeveld shale resulting in two short stretches, about 2 km long each, of sandy substratum, one in the upper-middle and one in the lower-middle reaches. Natural Fynbos is the predominant vegetation on the sandstone whereas the shales are extensively utilised for agriculture (fruit farming), the riparian vegetation in these reaches consisting mainly of alien trees (mostly *Acacia* spp) and reeds (*Typha* spp, *Phragmites* spp and *Prionium serratum*, the palmiet "reed"). The river is impounded five times within the first 40 km and then runs freely over the next 30 km to enter the sea via a normally open-mouthed estuary between the coastal towns of Betty's Bay and Kleinmond (Figure 1). Two of the impoundments on the system, both bottom-release impoundments, were chosen for

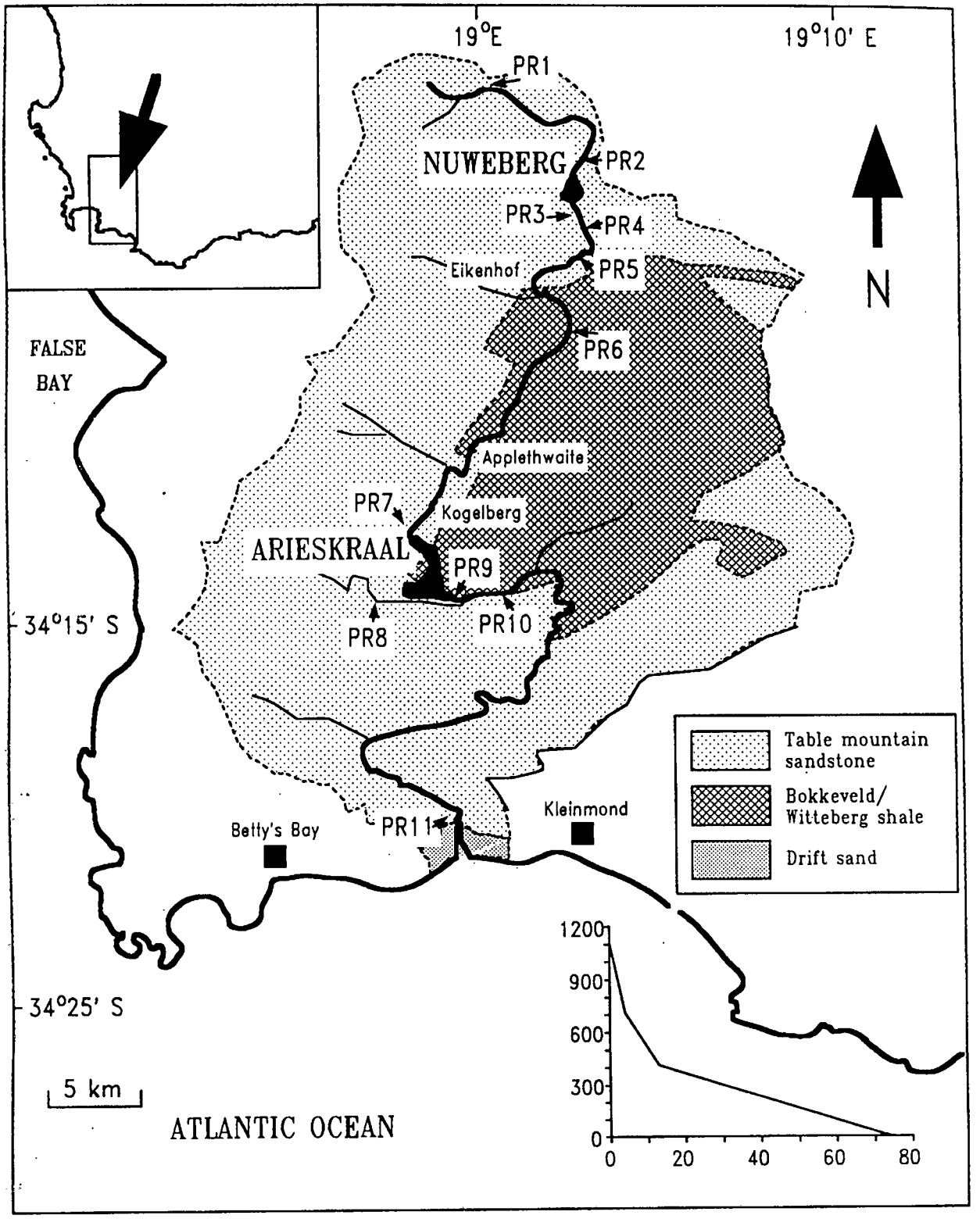


Figure 1: Map showing the location of the Palmiet River, the study sites, the underlying geology and the gradient.

extensive study viz. Nuweberg (uppermost impoundment, upper reaches) and Arieskraal (lowermost impoundment, middle reaches), as they provided reasonable lengths (7 km and 37 km, respectively) of downstream reaches over which recovery distances could be investigated and they occur in the least disturbed portions of the river, the major perturbations to the system being the impoundments themselves. The other three impoundments Eikenhof, Applethwaite and Kogelberg, are situated between Nuweberg and Arieskraal (Figure 1). Kogelberg, only about 1 km above Arieskraal, is the lower reservoir of a pump-storage scheme which was completed in 1987.

METHODS AND MATERIALS

Benthic macroinvertebrates were collected from "stones in current" (Chutter, 1968) using 0.1 m^2 modified box sampler with 80 μm-mesh netting (King, 1981). Three replicate samples were collected bimonthly from February 1987 to April 1988 at six sites (PR1, PR2, PR4, PR7, PR9, & PR10: Figure 1) on the Palmiet River and one site (PR8) on the Klein Palmiet, a tributary from which water is abstracted into Arieskraal (Figure 1). Although a total of 11 sites (Figure 1) were sampled on the river for physico-chemistry, particulate transport and macroinvertebrate drift (respectively Papers I, II & III, this thesis) sites PR3, PR5, PR6 and PR11 did not contain suitable riffle stretches for "stones in current" benthic samples to be taken. Samples were preserved in 5% formalin and stored in 1% phenoxitol. In the laboratory the samples were split into three size fractions to facilitate sorting: 80-250 μm, 250-950 μm and >950 μm. The 80-250 μm sample contained very few animals and the sorting effort far outweighed the information gained. Thus this fraction was excluded and results reflect all macroinvertebrates that did not pass through a 250 μm-mesh sieve. Animals were identified to the lowest taxonomic level possible considering the number of samples, and time and manpower constraints. Since many species of aquatic invertebrates have not been described in South Africa (King *et al.*, 1988), identification beyond generic level is seldom possible. For two of the main groups, ephemeropterans and trichopterans, identification to species level was possible and the community structure, represented as percent by number of each species of the total at each site, is presented as pie diagrams. Diptera and Coleoptera were identified using Pennak (1978), Ephemeroptera

using Barnard (1932), Plecoptera using Barnard (1934), and Trichoptera using Scholtz and Holm (1985) and K.F.M. Scott (unpubl. key to the Trichoptera).

Replicate samples were pooled to provide numbers per 0.3 m^2 and multiplied up to give numbers m^{-2} for each site and date. These values were used to determine the Shannon index of diversity and for two-way indicator species analysis (TWINSPAN) (Hill, 1979).

TWINSPAN, a FORTRAN programme recommended for hierarchical classification because of its effectiveness and robustness (Gauch, 1982), was used to group all the benthic samples on the basis of species abundance. The TWINSPAN programme first constructs a classification of the samples, and then uses this classification to obtain a classification of the species according to their ecological preferences. The two classifications are then used together to obtain an ordered two-way table that expresses the species' synecological relationships as succinctly as possible (Hill, 1979).

To quote "There are three ordinations involved:

1. The primary ordination (reciprocal averaging), which is divided to obtain an initial, crude dichotomy;
2. The refined ordination, which is derived from the primary ordination through the identification of differential species; and
3. The indicator ordination, based on a few of the most highly preferential species.

The refined ordination is normally used to determine the dichotomy. The indicator ordination is essentially an appendage, put there for the convenience of users who want a succinct characterisation of the dichotomy." (Hill, 1979).

Median numbers per unit area for each site were used to determine community structure and graphed in pie diagrams in terms of number of individuals as a percent of the total number per sample per site. Median values were chosen as they represent a good indication of base-flow trends and are least affected by extreme conditions such as droughts and floods (Byren and Davies, 1989; O'Keeffe *et al.*, 1990). The values of the variables downstream of the impoundment are said to increase or decrease with respect to the "above-impoundment" values.

RESULTS

A total of 79 macroinvertebrate taxa was found in the benthic samples of the Palmiet River (Appendix A). The species and genera were grouped to family level and the median numbers m^{-2} per site for each family are given in Table 1. Those taxa which were present at a particular site but whose median number m^{-2} was zero are recorded with a "+" in Table 1. The chironomid larvae had the highest density at each site with the highest median of 72 267 m^{-2} at site PR4, 0.5 km below Nuweberg. Site PR4 also showed the highest total invertebrate density with a median of 61 240 m^{-2} and a maximum of 459 200 m^{-2} (Figure 2). Ephemeropteran and simuliid densities decreased below Nuweberg (from 805 m^{-2} above the impoundment to 133 m^{-2} below and 364 m^{-2} above to 27 m^{-2} below respectively) but increased below Arieskraal (from 549 m^{-2} above to 622 m^{-2} below and 637 m^{-2} above to 1390 m^{-2} below respectively; Table 1). The reverse occurred for chironomid and hydropsychid larvae: below Nuweberg chironomids increased from 3 092 m^{-2} above to 72 267 m^{-2} below and hydropsychids from 3 m^{-2} above to 377 m^{-2} below, whereas below Arieskraal these two types of larvae decreased from 3 468 m^{-2} above to 2 985 m^{-2} below and from 339 m^{-2} above to 220 m^{-2} below respectively. Below Nuweberg increases in density also occurred for Hydracarina (40 m^{-2} above to 750 m^{-2} below), Copepoda (42 m^{-2} above to 587 m^{-2} below) and Cladocera (355 m^{-2} above to 853 m^{-2} below). Tricladida increased markedly from 39 m^{-2} above to 500 m^{-2} below Arieskraal, but returned to a fairly low level (30 m^{-2}) within 3 km of the impoundment.

Of the 58 taxa analysed 40 either increased or decreased in median number below one or both of the impoundments. The other 18 taxa were either absent or "rare" both above and below one or both impoundments (Table 1). Twenty four of the 40 taxa which increased or decreased below one or both impoundments either increased from zero to "rare" or "rare" to a median >0 (median=0) or decreased from "rare" to zero, or a median >0 to "rare". For the remaining 16 taxa which increased or decreased below one or both impoundments, the two reservoirs induced the opposite response in 13 taxa. Of all the taxa which increased or decreased in the same way below both impoundments only two, the Chaoboridae and the

Table 1: Median numbers m^{-2} per site for each taxon. Those taxa which were present at a particular site but whose median number m^{-2} was zero are recorded with a "+".

TAXON \ SITE	1	2	4	7	9	10	8
Plecoptera	132	22	7	2	+	3	143
Ephemeroptera	537	805	133	549	622	737	580
Simuliidae	55	364	27	637	1390	90	163
Chironomidae	714	3092	72267	3468	2985	8187	3890
Rhagionidae	14	15	+	+		+	3
Ceratopogonidae	2	4	+	+	+		10
Empididae		+	+	+	+	20	
Tabanidae		+			+		
Tipulidae			+	+			
Chaoboridae		+	+	+	19	+	
Blephariceridae	+						
Culicidae		+		+			
Anthomyidae						+	
Megaloptera	+	4	+	+		+	+
Hydropsychidae	+	3	377	339	220	90	+
Ecnomidae	+	3		+	+	+	40
Hydroptilidae	+			7	3	3	3
Leptoceridae	+	3	53	+		+	7
Philopotamidae	+						+
Petrothrincidae	5						+
Glossosomatidae				+			+
Other Trichoptera	+	+	+	+			+
Lepidoptera							+
Thysanoptera			+				
Coleoptera (adults)	23	19	13	+	+	+	160
Helodidae	47	19	+				80
Elmidae-A	7	3	87	9	2	40	80
Elmidae-B		+					30
Elmidae-C	87	234	27	+	+	27	493
Corixidae		+	+				
Gerridae		+					
Hydraenidae	+						+
Hydrophiliidae		+		+			
Dytiscidae				+			
Belostomatidae							+
Notonectidae		+					
Naucoridae							+
Hebridae							+
Other Hemiptera		2		+			3
Aeshnidae	+		+	8	+	+	+
Gomphidae		+					+
Zygoptera	+	+					3
Hydracarina	22	40	750	4	12	80	1053
Oligochaeta	75	1150	80	29	145	50	263
Nematoda	+	60	27		29	23	147
Tricladida	+	+	33	39	500	30	+
Nematomorpha			+				
Hirudinea	+						
Hydra		+	+	+	+	+	+
Copepoda	22	42	587	1837	212	107	410
Cladocera	11	355	853	1185	160	30	1107
Ostracoda	+	+		397	+	+	13
Amphipoda	9				+		53
Isopoda							+
Decapoda				+			+
Gastropoda				30	+	+	
Collembola	+	+		+	+		+
Rotatoria				+			+
TOTAL NUMBER OF TAXA	38	43	29	40	30	31	48

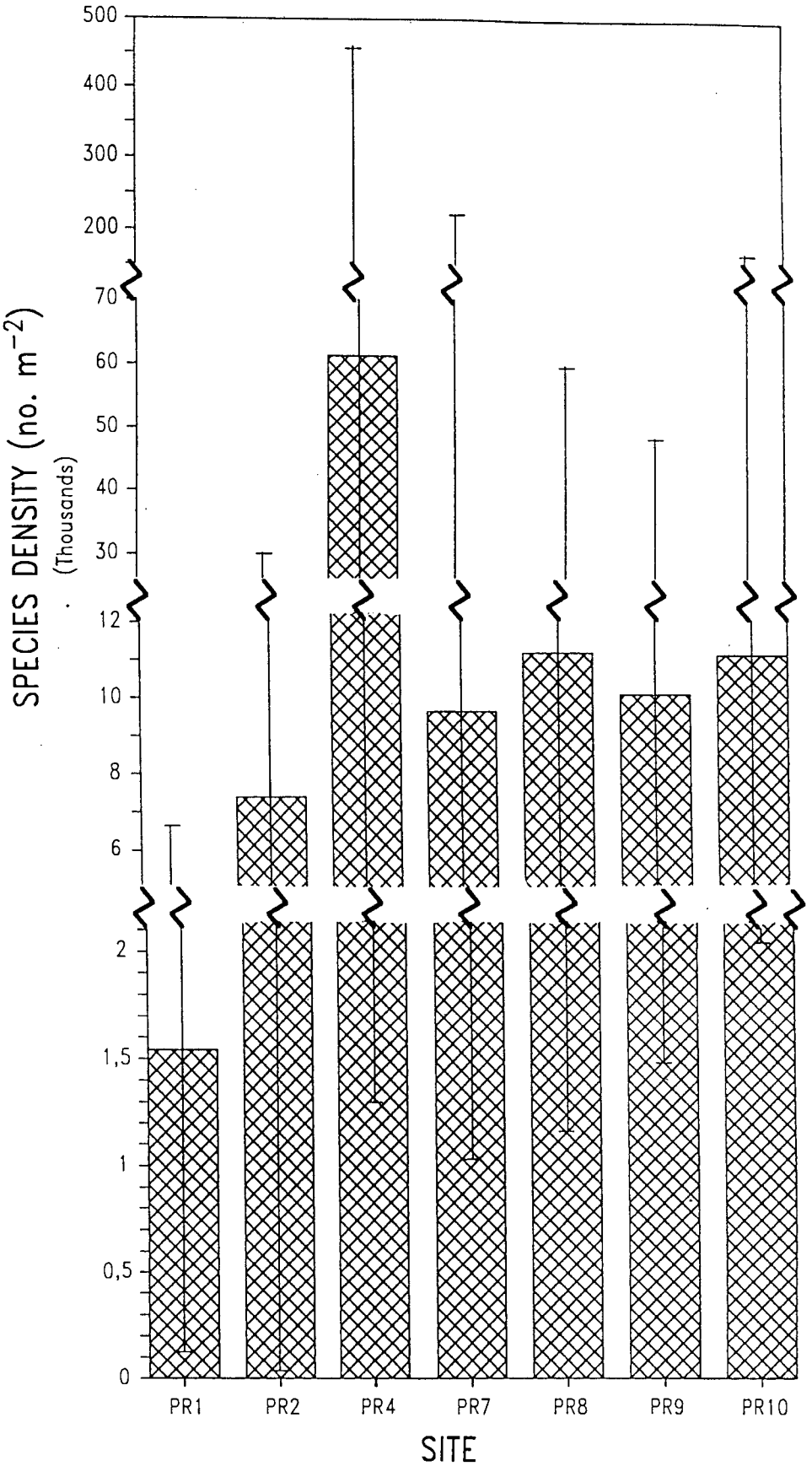


Figure 2: Total invertebrate density (median number m^{-2}). Vertical lines indicate the range (max/min).

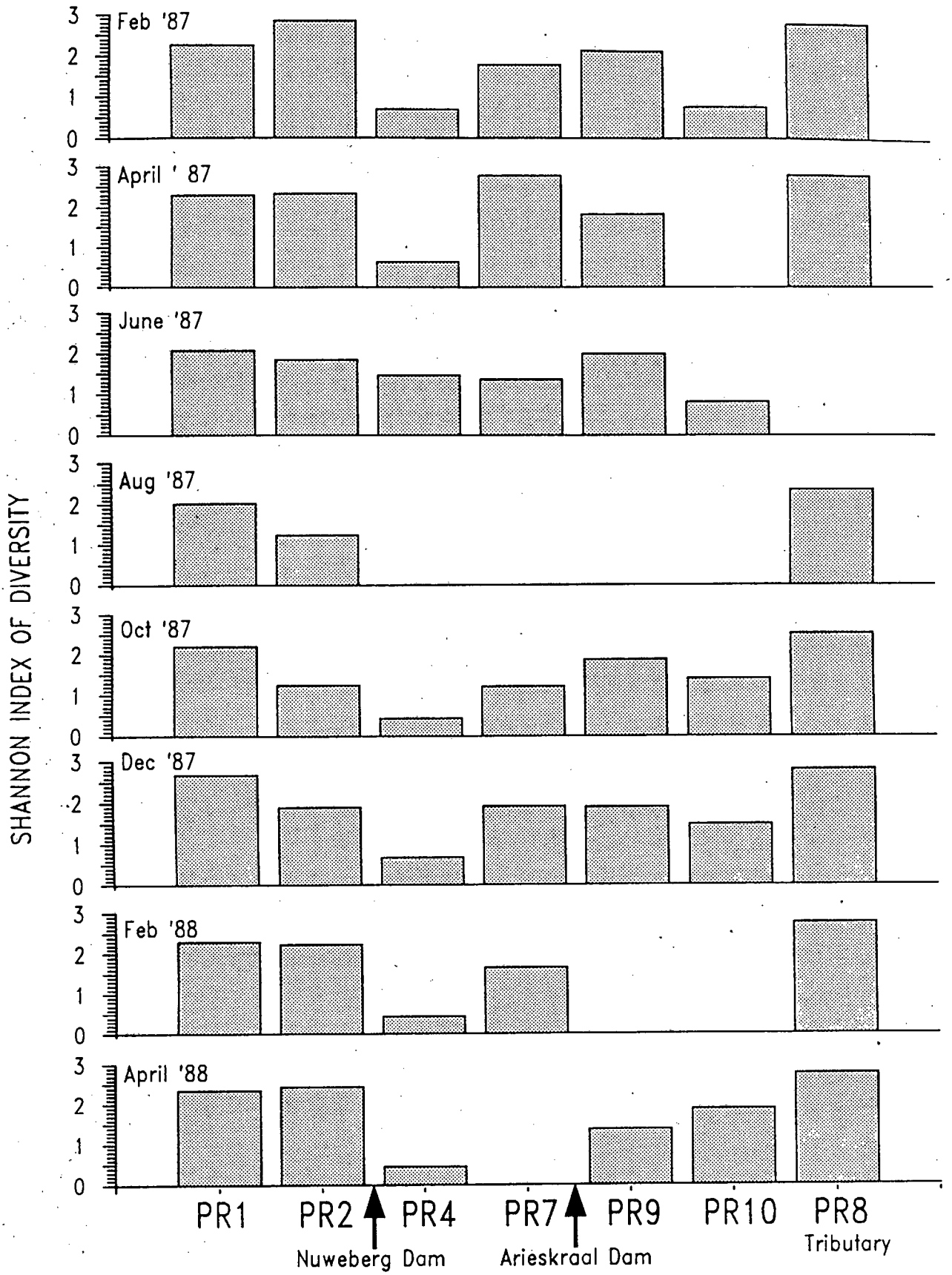


Figure 3: Downstream changes in benthic macroinvertebrate species diversity(Shannon index) for each survey.

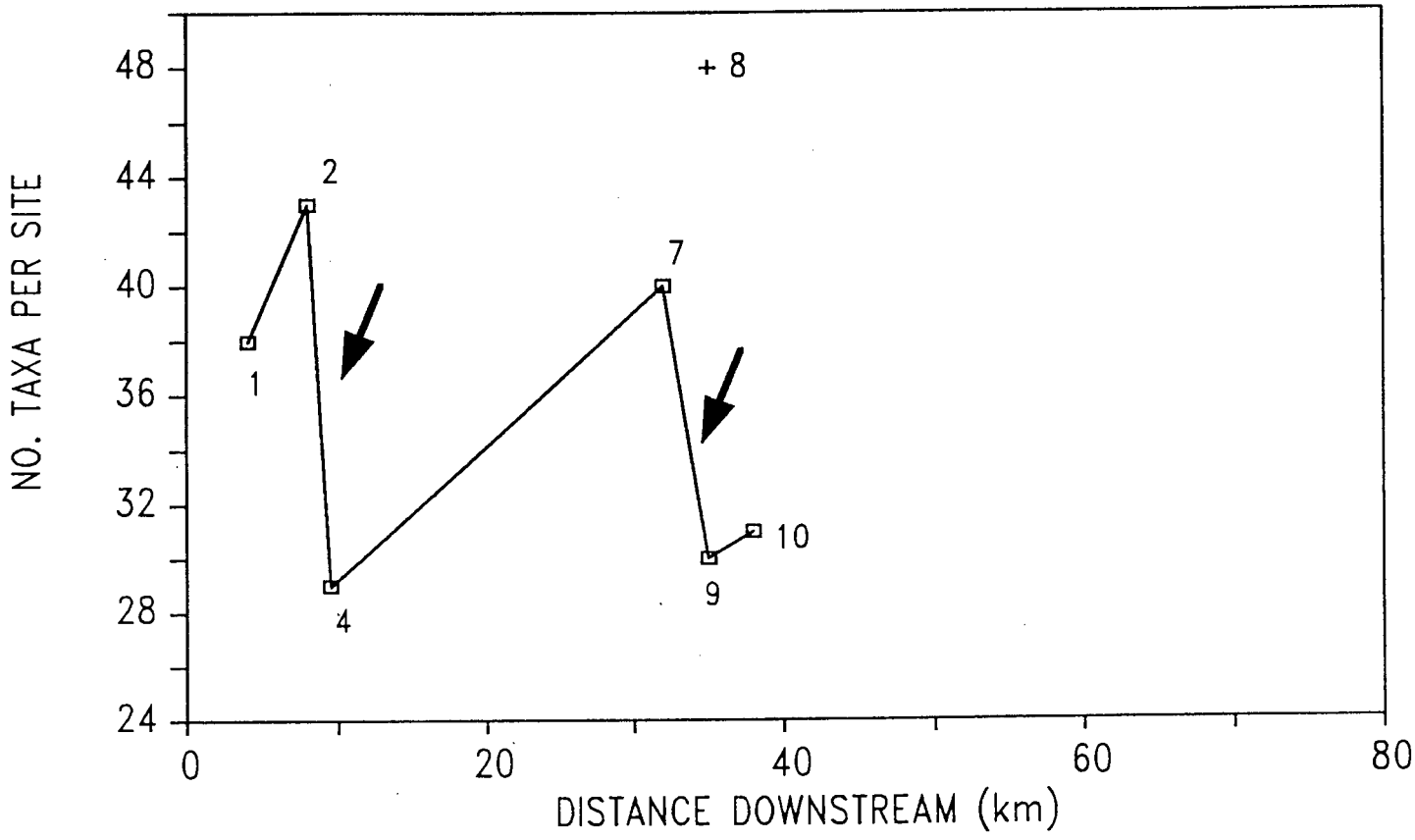


Figure 4: Downstream changes in taxonomic richness. The numbers in the graph refer to the study sites and the arrows indicate the positions of the dams.

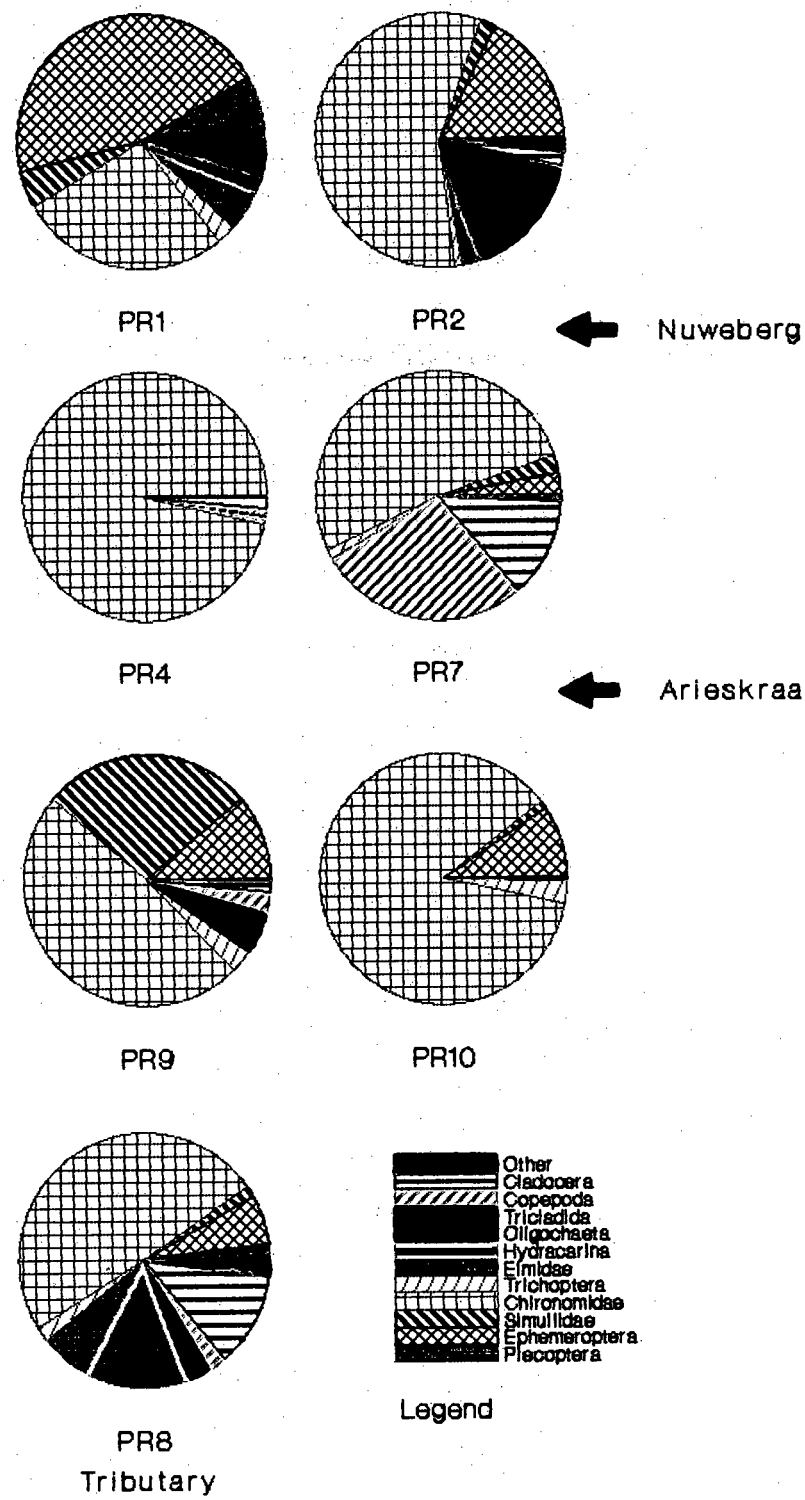


Figure 5: Community structure pie-diagrams which represent the median percentage of each taxon of the total median number of organisms found in the samples.

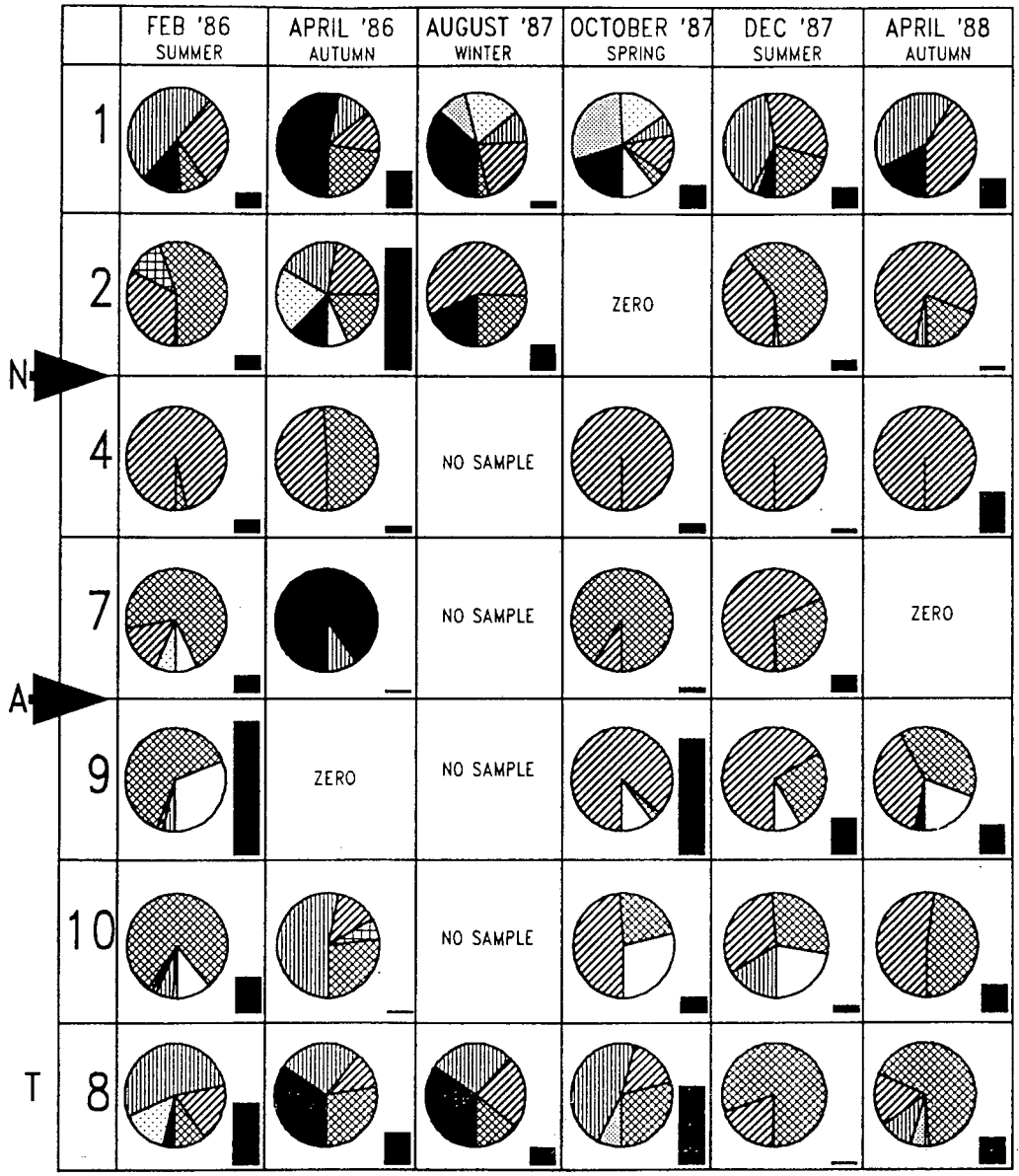
Tricladida, showed an increase in numbers. All the other taxa decreased to "rare" or zero below both impoundments: i.e they virtually disappeared (Table 1).

Species diversity (Shannon index: Figure 3) was highest in the upper reaches and in the tributary, was low in the lower upper reaches and increased in the lower middle reaches. Species diversity decreased noticeably below Nuweberg in all surveys except in mid-winter 1987 (6/87). The change in species diversity immediately below Arieskraal varied greatly over time, but in most cases diversity decreased over the 3 km stretch of river below Arieskraal from PR9 to PR10.

Benthic macroinvertebrate taxonomic richness (Figure 4) was highest, 48 taxa, at the control site on the Klein Palmiet, one of the major tributaries of the Palmiet River which enters the river between sites 9 and 10, about 0.5 km downstream of Arieskraal. Taxonomic richness decreased markedly below both impoundments and did not recover within the three kilometre sample stretch below Arieskraal.

As far as community structure is concerned (Figure 5), the Chironomidae predominated at all sites except site 1, the pristine headwaters, where ephemeropterans comprised the highest percentage (45%). The community structure pie-diagrams (Figure 5) show that below Nuweberg (PR4) the chironomid larvae component of the population increased from 57% to 96% of the total population. Below Arieskraal (PR9) the simuliid component of the community increased from 2% to 28% and the Chironomidae and Simuliidae comprised 77% of the total. Within three kilometres (PR10) the Chironomidae again became dominant, comprising 86% of the total.

The proportion of different genera/species within the ephemeropterans and trichopterans for each site are shown in Figures 6 and 7. These community structure diagrams show the seasonal and downstream changes in community structure and species richness (pie-diagrams) and total number of organisms per sample (vertical bars) for the two major groups of macroinvertebrates in the Palmiet river for which classification to genus/species level was possible (Figures 6 & 7). Species richness was highest at the two pristine sites (PR1 & PR8) for the ephemeropterans but only at PR8 for the trichopterans. Both these pristine sites contained organisms which were found nowhere else in the river course.



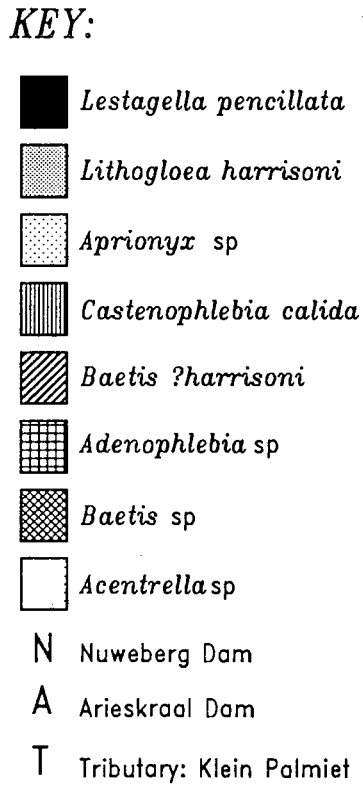


Figure 6: The proportion of different genera/species within the ephemeropterans for each site. The vertical bars indicate the total number of organisms in each sample. Zero = no ephemeropterans found at that site; no sample = no sample available due to experimental problems such as e.g. heavy flooding.

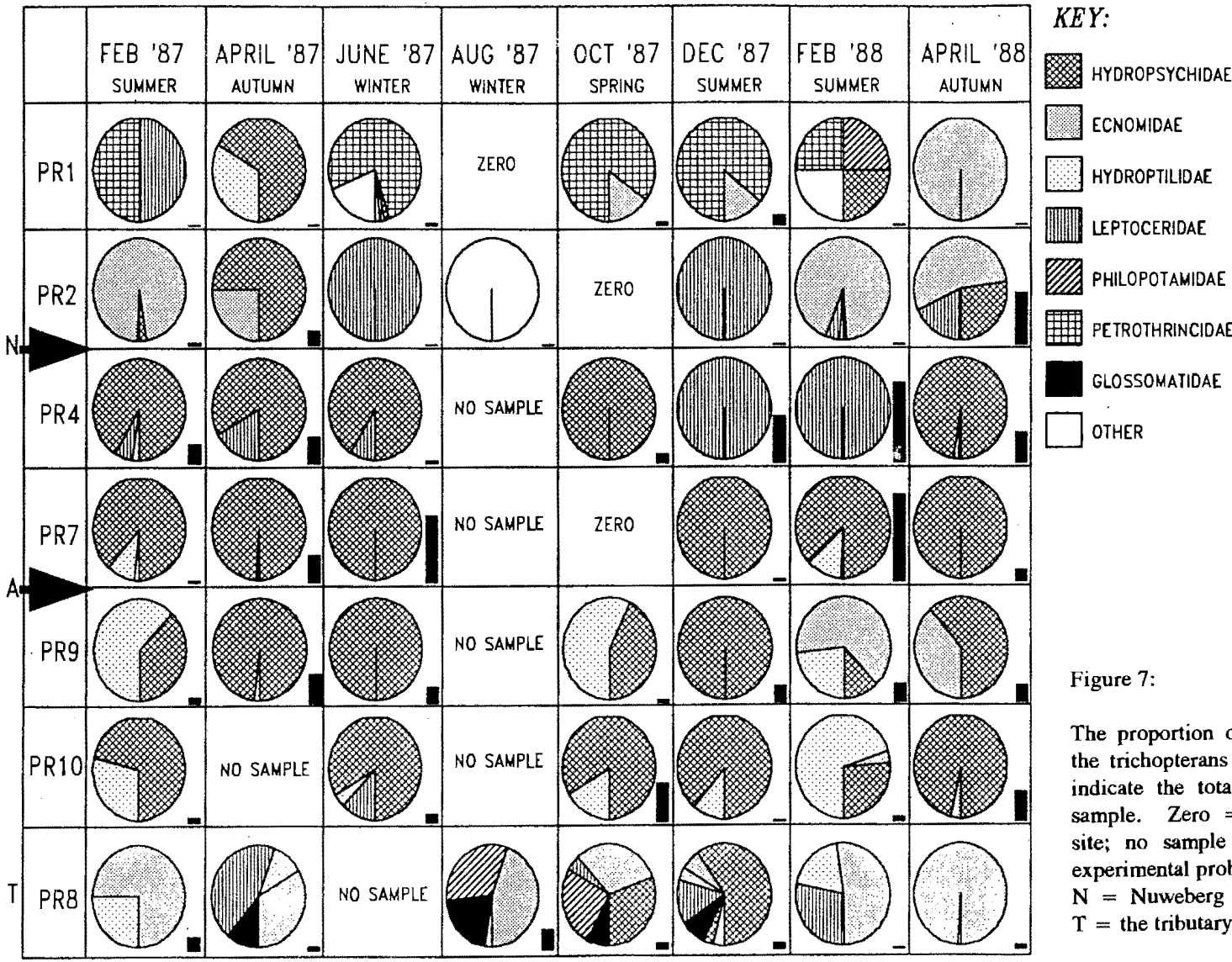


Figure 7:

The proportion of different genera/species within the trichopterans for each site. The vertical bars indicate the total number of organisms in each sample. Zero = no trichopterans found at that site; no sample = no sample available due to experimental problems such as e.g. heavy flooding. N = Nuweberg Dam, A = Arieskraal Dam and T = the tributary, the Klein Palmiet.

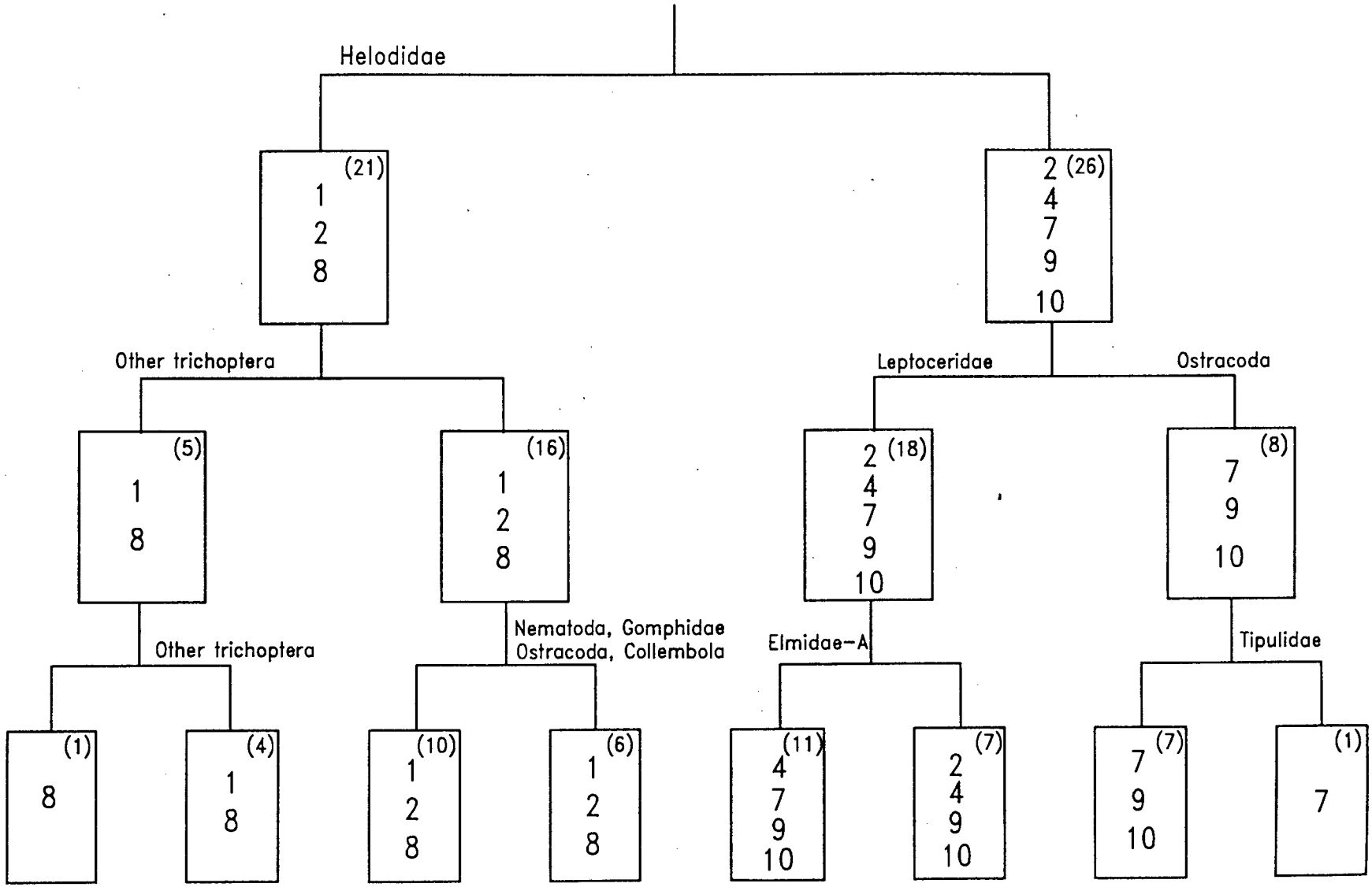


Figure 8: Classification of invertebrate samples by site using Two-way indicator species analysis (TWINSPAN). The numbers in the blocks refer to the sites represented in each group; major indicator species for each division are shown and the number of samples in each group is given in perentheses in the top right-hand corner.

Species richness in these two groups usually decreased below the impoundments, especially below Nuweberg where there was often only a single species present (PR4, Figures 6 & 7). Trichopteran numbers were lowest at the pristine sites, increased markedly below Nuweberg, increased still further at site PR7 and the decreased below Arieskraal (Figure 7). In the middle reach sites (4, 7, 9 & 10) the community was dominated by Hydropsychidae, predominantly *Cheumatopsyche* sp (Figure 7b).

Two-way indicator species analysis (TWINSPAN), taken to level 4, showed certain distinctions between sites (Figure 8). At level 2 two distinct groups occurred: Division 2 comprising almost all the samples from sites 1, 2 and 8 (except two samples from site 2) with the indicator species being the Helodidae; and division 3 comprising all the samples from sites 4, 7, 9 and 10 plus the two remaining samples from site 2. Further division of the predominantly pristine, above-impoundment, samples (sites 1, 2 & 8) registered indicator species such as the less common trichopterans (other Trichoptera), Nematoda, Gomphidae, Ostracoda and Collembola. The disturbed sites below impoundments were divided further by indicator species such as leptocerids, ostracods, tipulids and Elmidae sp A.

DISCUSSION

The numbers of taxa found in the Palmiet River may not entirely be comparable with other studies due to differences in methodology and to the existence of some unsorted families. However, although there are various methods of collecting, sorting and identifying benthic macroinvertebrates, and accepting that most analyses include some unsorted families, an attempt is made to put the Palmiet River in context with other river systems around the world. The total of seventy nine taxa recorded was fairly large compared with the numbers of taxa recorded in other studies. Only 24 taxa showed a median number m^{-2} greater than zero at more than one site, ie. most taxa were "rare". These values compare well with the range of taxa recorded in other studies: Zeiser (1985) recorded 92 taxa in Rocky mountain stream, Santa Fe, and Novotny (1985), 74 taxa on the Barren River, Kentucky. Spence and Hynes (1970) used 24 major taxa in their study on the Grand River, Ontario, and Corkum (1989) used 19 taxa for analysis of 100 river sites in northwestern North America. Harrison and Elsworth (1958) working on the Berg River, south-western Cape, South Africa, found a

total of 237 species (155 excluding all chironomid species) including marginal vegetation and sandy-bed samples and 122 species (72 excluding all chironomid species) in the stones in current. Since the chironomidae were not identified in this study the figure of 72 species for "stones in current" excluding all chironomid species is comparable with the 79 taxa found in the Palmiet River.

The SDC and benthic macroinvertebrates in the Palmiet River

The SDC (Ward and Stanford, 1983a) predicts that biotic diversity will decrease slightly below an upper reach impoundment and decrease markedly below a middle reach impoundment because the unstable environmental conditions characteristic of mountain streams reduce the stabilising effect of the impoundments as well as allowing for a fairly rapid re-establishment of the unstable conditions that facilitate high biotic diversity (Intermediate Disturbance Hypothesis: Connell, 1978; Ward and Stanford, 1983b). Biotic diversity is not defined in the SDC and is interpreted here as both taxonomic richness and as Shannon diversity, a diversity index that takes into account not only species richness but also the number of individuals per species. The way in which benthic macroinvertebrate diversity (Shannon index as well as taxonomic richness) changes downstream of the impoundments on the Palmiet River, and how the diversity compares with the predictions of the SDC will be discussed below:

a) taxonomic richness

The marked decrease in benthic taxonomic richness below both impoundments is a common occurrence below dams (Ward and Stanford, 1979; Stanford and Ward, 1984). Zeiser (1985) recorded an increase from 26 to 29 taxa below Santa Fe Lake, however. The more stable conditions created below the impoundment favour the growth of certain organisms, often pest species such as blackfly and midge larvae (e.g. Ward and Stanford, 1979; Munn and Brusven, 1991). In the Palmiet River there were large increases in the populations of chironomid larvae and caddisfly larvae below Nuweberg and of blackfly larvae below Arieskraal. Since conditions were not suitable for benthic sampling at site 11, just above the estuary, it is not known whether or not the taxonomic richness increases as the river flows through the undisturbed lower reaches. However, there was only partial recovery in drift taxonomic richness before reaching the estuary (Paper III, this thesis) and, since there

was a significant linear relationship between drift and benthic taxonomic richness (Paper III, this thesis), it is possible that benthic taxonomic richness will also recover partially before the estuary.

b) diversity

The decrease in species diversity below impoundments is due to the more stable environmental conditions created below the impoundment as a result of a more constant, predictable flow rate and temperature, and has often been recorded in the literature (Coleman, 1978; King and Tyler, 1982; Walker, 1985; Zeiser, 1985; Munn and Brusven, 1991). In the Palmiet River, benthic macroinvertebrate taxonomic richness decreased below both impoundments, whereas Shannon diversity decreased markedly below the upper reach impoundment (Nuweberg), appeared to increase slightly below the middle reach impoundment, and decreased over the next 3 km.

High biotic diversity in streams with unpredictable/harsh environments is a prediction of the Intermediate Disturbance Hypothesis (Ward and Stanford, 1983b). As regards the effects of low pH on diversity, Graça *et al.* (1987) compared two rivers in Portugal and found higher diversity in the naturally acid river yet higher abundance in the alkaline river. However, Smith *et al.* (1990), in a study on three low-order woodland streams in an area known to be impacted by acid rain, found that total invertebrate density was not lower at acidic sites and that although generic richness and diversity were correlated with pH they were not significantly lower at acid sites. In the Palmiet River both taxonomic richness and diversity are highest in the upper reaches where macroinvertebrate densities are lowest. The TWINSPAN analysis clearly distinguishes the pristine headwater sites and the pristine tributary from the rest in terms of certain headwater species viz. Helodidae and the less common Trichoptera (other Trichoptera). The extremely acid, cool conditions found in the headwater and tributary sites (PR1 & PR8), which are subject to large extremes in flow rate, are a fairly harsh environment which provides a large number of different habitats resulting in small populations of a wide variety of species.

Macroinvertebrate density

The distribution and abundance of species can be determined by tolerances to extremes of physical conditions (Peckarsky and Dodson, 1980). High macroinvertebrate density is a

common feature below dams (Ward, 1976; Ward and Stanford, 1979; Brusven, 1985; Zeiser, 1985, Mackay and Waters, 1986; Munn and Brusven, 1991), but a decrease in density can also occur (Radford and Hartland-Rowe, 1971; Trotzky and Gregory, 1974). Spence and Hynes (1971) attribute the increase in certain organisms below impoundments to an increase in the availability of detritus, a lag in the summer temperature rise, a decrease in the annual temperature range and the alteration of other environmental factors (see Byren and Davies, 1989). The high densities of certain taxa, especially of chironomids, compared with other taxa found in the Palmiet River and particularly at sites 4,7 & 10, seem to indicate that the fairly stable conditions of flow and temperature which exist below the impoundments (Byren and Davies, 1989) adds to their success. The site on the the tributary, the Klein Palmiet River (PR8), provides a more temperate environment, with high species density (numbers m^{-2}), the highest taxonomic richness and species diversity of all sites sampled, and dense growths of algae and submerged aquatic macrophytes on the substratum (B. A. Gale, pers. obs.).

Of interest is the difference in the response of the macroinvertebrate communities below the upper and middle reach impoundments. The upper reach impoundment transforms a diverse, fairly pristine stream into a disturbed community consisting of a much higher density but lower diversity of organisms. Many of the organisms which thrive in the clear, acid, Cape mountain streams are virtually eliminated below Nuweberg, whereas organisms prominent in disturbed/polluted systems (e.g. blackfly and midge larvae) as well as species of lentic origin (e.g copepods and cladocerans) increase by between 58% and 99%. Below Arieskraal, on the other hand, many organisms that are common below impoundments (e.g chironomid and hydropsychid caddisfly larvae) actually decrease in density from the upstream site. This is probably due to the disturbed nature of the above-impoundment site (PR7) which, although only 0.5 km above Arieskraal, is 0.5 km below a newly constructed impoundment, Kogelberg (Figure 1). The TWINSPAN analysis groups site 7 along with all the other sites below impoundments.

It is impossible to determine 'recovery' distances (*sensu* O'Keeffe *et al.*, 1990) for individual benthic macroinvertebrate taxa as not only impoundment but also changes in zones down the river will affect benthic invertebrate community composition. Since

Nuweberg is only approximately 1 km long and is situated within the mountainous upper reaches of the river, 9 km from the source of the river, the downstream change in community composition is presumed to be entirely impoundment-induced. Although Arieskraal is situated within the middle reaches of the river it is about 3 km long and is only 1 km below an upstream impoundment, Kogelberg. Thus, because there was no useful upstream site to compare with, the direct effect of the impoundment on downstream community structure is difficult to determine.

CONCLUSION

The changes in the community structure of benthic macroinvertebrates in the Palmiet River as a result of impoundment has highlighted some difficulties in predicting the biological impacts of impoundment. The position of the impoundment along the river continuum is not the only factor contributing to downstream alterations. The existence of other impoundments in the system may reduce diversity to very low levels and another impoundment may even partially 'reset' the biotic diversity in the river, as is implied by the increased Shannon diversity at site 9, below the lowermost impoundment, Arieskaal. Arieskraal is the lowermost reservoir of a series of five impoundments within 20 km of river. The site upstream of Arieskraal is already impacted, having a lower Shannon diversity than the site immediately below Arieskraal, and the impoundment could be said to partially 'reset' the system along its continuum. The 34 km of undisturbed, pristine environment through which the remainder of the river flows, before entering the estuary, will probably 'reset' the system close to its original state.

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Appendix A: Macroinvertebrate taxa recorded in the benthic samples of the Palmiet River.

Diptera
Chironomidae
Simuliidae
Rhagionidae
Ceratopogonidae
Empididae
Tabanidae
Tipulidae
Chaoboridae
Blephariceridae
Culicidae
Anthomyidae

Ephemeroptera
Lestagella pencillata
Lithogloea harrisoni
Aprionyx sp
Castenophlebia calida
Baetis ?harrisoni
Adenophlebia sp
Baetis sp
Acentrella sp

Plecoptera
Aphanicerca spp

Trichoptera
Cheumatopsyche sp
Macrostemum capense
Other hydropsychidae
Parecnomina sp
Ecnonomus sp
Ecnonomus thomasseti
Hydroptila capensis
Orthotrichia barnardii
Oxyethira volocipes
Trichosetodes sp
Leptico helicotherca
Athripsodes sp
Other leptoceridae
Dolophilodes sp
Petrothrincus circularis
Agapetus sp
Stenopsyche ulmeriana
Psychomyidae
Polycentropodidae

Coleoptera
Helodidae
Elmidae spA
Elmidae spB
Elmidae spC
Hydraenidae
Hydrophiliidae
Dytiscidae
Gyrinidae
Other (unidentified)

Hemiptera
Notonectidae
Naucoridae
Hebridae
Belostomatidae
Corixidae
Gerridae
Other (unidentified)

Odonata
Anisoptera
Aeshnidae
Gomphidae
Zygoptera

Annelida
Oligochaeta
Hirudinea:
Glossiphonia sp

Nematoda

Tricladida
Dugesia sp

Cnidaria
Hydra spp

Crustacea
Metadiaptomus purcelli
Thermocyclops emini
Ceriodaphnia sp
Bosmina sp
Paramelita nigroculus
Potomonautes perlatus
Isopoda
Ostracoda

Arachnida
Hydracarina sp

Gastropoda
Ferrissia sp
Lymnaea sp

Lepidoptera
Pyralidae

Megaloptera
Corydalidae

Nematomorpha

Collembola

Rotatoria

A COMPARISON BETWEEN SOME LIMNOLOGICAL CHARACTERISTICS WITHIN TWO IMPOUNDMENTS AND THE UPSTREAM AND DOWNSTREAM RIVERINE CONDITIONS.

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COMPARISON BETWEEN SOME LIMNOLOGICAL CHARACTERISTICS WITHIN TWO IMPOUNDMENTS AND THE UPSTREAM AND DOWNSTREAM RIVERINE CONDITIONS.

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ABSTRACT

Some limnological characteristics of the inflow to and outflow from two man-made lakes were compared with those at the respective receiving and discharging ends. Two impoundments on the Palmiet River, Nuweberg and Arieskraal, were sampled in January (mid summer) and June (mid winter) 1988, in order to clarify the direct effects of stream-lake-stream interactions. Certain physical, chemical and biological parameters were measured in the inflow and outflow, and at three different depths (top, middle and bottom) near the receiving and discharging ends of both impoundments. A comparison of the surface water at the receiving end of each impoundment versus the corresponding inflowing water showed no significant differences ($P<0.05$) for Arieskraal. For Nuweberg the only significant differences were for TSS in summer and cyclopoid copepods and copepod nauplii during winter. A comparison of the bottom water at the outflowing end of each impoundment versus the outflow water below each impoundment only showed significant differences for one variable, dissolved oxygen, for Nuweburg in summer and for Arieskraal in both summer and winter. Zooplankton numbers per unit volume varied greatly in many of the samples and there was little similarity between the numbers in the inflow to those at the receiving end and between the numbers in the outflow to those at the discharging end of the two impoundments. Nuweberg is dominated by *Thermocyclops emini* and *Ceriodaphnia* sp, whereas Arieskraal populations are dominated by *Metadiaptomus purcelli* and copepod nauplii. No calanoid copopods (*M. purcelli*) or *Bosmina* spp were collected from Nuweberg and there was a complete disappearance of *Chaoborus* sp in winter. Zooplankton taxonomic richness was generally higher in Arieskraal than in Nuweberg. In most samples richness was greater in summer than in winter. In all cases the inflow to Nuweberg had lower densities than in the receiving end of the impoundment whereas in some cases the inflow to Arieskraal showed higher densities of certain species than in the receiving end. In Nuweberg the species densities in the outflow corresponded well with the bottom water at the discharging end of the impoundment. Below Arieskraal all species, except *T emini*, showed higher densities in the outflow than in the bottom water at the discharging end. Canonical Correspondence Analysis (CCA) showed a good relationship between site ordination and environmental gradients. The physico-chemistry of the inflow and outflow closely reflect the within-impoundment conditions but bottom release impoundments severely alter the physico-chemical and biological characteristics of the river. The lake-stream-lake interaction is highly complex with numerous variables acting in a variety of different ways. There are many factors which need to be taken into account if a valuable ecological model predicting the downstream effects of impoundment is to be attempted.

1980; Clarke 1989) (Figure 1). This 74 km long river is impounded five times within the first 35 km and then runs freely over the next 39 km to enter the sea via a usually open-mouthed estuary between the coastal towns of Betty's Bay and Kleinmond (Figure 1). The area lies within a highly seasonal winter (April to September) rainfall, mediterranean climatic region. Two of the impoundments on the system were chosen for extensive study: Nuweberg (the uppermost impoundment, upper reaches) and Arieskraal (the lowermost impoundment, middle reaches), as they occurred in the least disturbed portions of the river, the major perturbation to the system being the impoundments themselves.

Nuweberg is situated approximately 9 km from the source and is fed by a stream that originates in open-canopied mountain fynbos, a low, fire-adapted, sclerophyllous shrubland, and then passes through the pine plantations of the Nuweberg State Forest. The impoundment has an earth-fill wall about 25 m high with a bottom release outlet valve about 5 m above the river bed and a maximum capacity of 3.9×10^6 m^3 (Clarke 1989). The water is released on demand to replenish the next impoundment on the system, Eikenhof, an irrigation water supply dam.

Arieskraal, about 32 km from the source, borders the south-eastern boundary of an extensively cultivated fruit-growing region, and supplies irrigation water to the surrounding fruit farms. It is fed by a river that, on leaving Eikenhof, has passed through the village of Grabouw (the only urban development on the river), and subsequently through two impoundments: Applethwaite, an irrigation supply structure, and Kogelberg, the lower reservoir of the Palmiet Pumped Storage Scheme. On leaving Kogelberg the river covers a mere 1 km through dense alien (mainly *Acacia* spp) riparian vegetation before it enters the head of Arieskraal. Arieskraal has a 26 m high concrete wall and a maximum capacity of 5.9×10^6 m^3 (Clarke 1989). The outlet structure consists of a 40 cm diameter flanged outlet valve (approx. 15 cm permanently open) about 2 m from the river bottom (i.e bottom release), and an irrigation draw-off pipe, attached to a pump, approximately 13 m from the bottom.

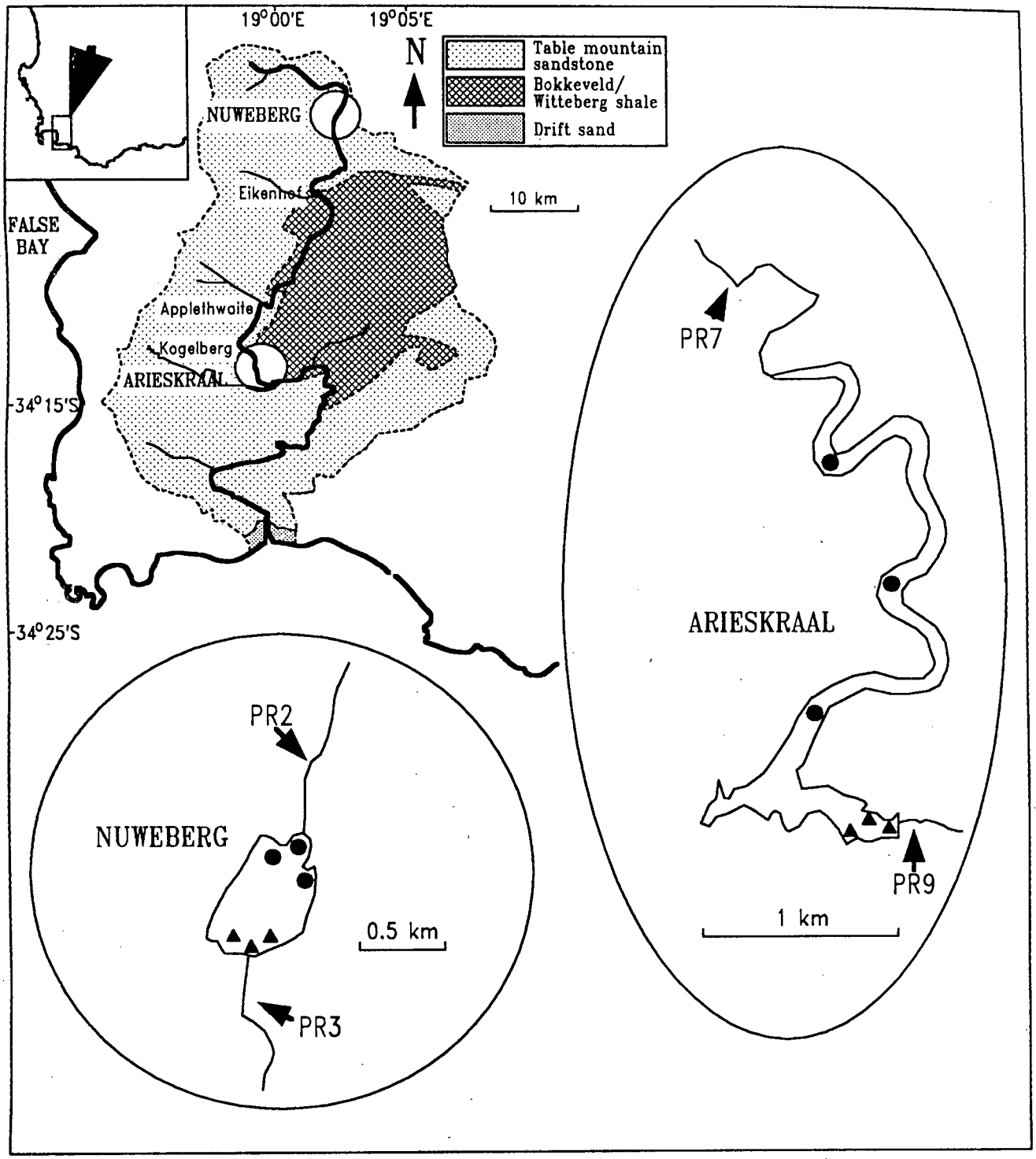


Figure 1: Map showing the Palmiet River Catchment, the position of the dams on the system and the approximate positions of all the sampling sites.

METHODS AND MATERIALS

A study of the physical, chemical and biotic conditions of the receiving and discharging water within two impoundments, Nuweberg and Arieskraal, was undertaken, and was compared with the conditions in the inflow and outflow water of the impoundments. Two sets of samples were collected: in January (mid summer) and June (mid winter) 1988. Each sampling period occurred over four days: Nuweberg on days 1 and 2 and Arieskraal on days 3 and 4. The water in the river above (inflow) and below (outflow) each impoundment was sampled on both of the days when the relevant dam was being sampled. Three sites were chosen near both the receiving and the discharging ends of each impoundment (Figure 1). Samples of water were taken at three different depths (top, middle and bottom) using an 8 *l*, messenger operated, Nissen sampling bottle, inserted four times at each site to provide a total of 32 *l* of water for each biotic sample and a fifth time to provide water for chemical analysis (i.e 40 *l* of water were collected at each of 18 different locations within each impoundment). Sampling began around noon each day to allow time for surface heating. Faunal samples were fixed in 5% formalin, returned to the laboratory and preserved in a 2% phenoxitol solution before being sorted, and the fauna identified and counted. Temperature, dissolved oxygen (DO), pH and conductivity were measured on site. Water for nutrient analysis, total suspended solids (TSS) and total dissolved solids (TDS) was filtered through an 80 μm-mesh net, stored in a bucket and returned to the shore. The water was then filterd through pre-weighed, pre-combusted, Whatman GF/F filters which trap particles down to 0.7 μm . The filter was stored for further TSS analysis. The filtrate was bottled in polythene containers pre-cleaned in 5% Extran^R solution (phosphate-free) and double-distilled water, frozen and returned to the laboratory for analysis. The physico-chemical and biotic samples taken and the methods used for analysis are tabulated in Table 1.

On the first day of sampling (for each lake) the drift in the inflow and outflow water was collected in a similar manner to the collection of plankton in the lakes (using the Nissen bottle). On the following day drift was collected using a drift net with a mouth opening of 0.048 m^2 and a tail of 50 cm. Samples of drift were collected over 5 minutes on each occasion and the current through the net was measured using an Ott C2 current meter

allowing calculation of the total volume of water passing through the net. By knowing the volume of water sampled and the zooplankton counts per sample the results can be calculated as numbers of individuals m^{-3} of water.

Table 1: Sample Analysis

Variable	Units	Method
Temperature	°C	Mercury thermometer
pH		Crison field pH meter
Dissolved Oxygen	%saturation	YSI dissolved oxygen meter
Conductivity	$\mu S\ cm^{-1}$	Crison field meter
Total Dissolved Solids	$mg\ l^{-1}$	A known volume of water (400 ml), filtered through a Whatman GF/F filter, is evaporated at 90 °C from pre-weighed glass beakers. The beakers are re-weighed and the difference calculated
Total Suspended Solids	$mg\ l^{-1}$	A known volume of water is filtered through a pre-weighed, pre-combusted, Whatman GF/F filter, dried at 60 °C for 48 h and re-weighed.
SRP	$\mu g\ l^{-1}$	Technicon Auto Analyser (Mostert, 1983).
Nitrite	$\mu g\ l^{-1}$	Technicon Auto Analyser (Mostert, 1983).
Nitrate	$mg\ l^{-1}$	Technicon Auto Analyser (Mostert, 1983).
Zooplankton	no. m^{-3}	4 x 32 *l* messenger operated Nissen bottle at required depth poured through 80um- mesh net, fixed in 5% formalin, preserved in 2% phenoxitol, and fauna sorted, identified and counted.

One-way analysis of variance (ANOVA: Zar, 1984), for all variables measured, was used to determine the relationship between the inflow vs receiving and outflow vs discharging ends of both impoundments, between the surface, middle and bottom waters at each station within the impoundments and the differences/similarites between the two impoundments.

CANOCO, a FORTRAN programme for canonical community ordination by partial, detrended or canonical correspondence analysis, principle components analysis and redundancy analysis, developed by Cajo J. F. Ter Braak (1987) was used to analyse the lake data and to interrelate this with environmental variables. The Canonical ordination technique (Canonical Correspondence Analysis or CCA) was chosen as the method which

best described the results obtained. This is a multivariate, direct gradient, analysis technique, which attempts to explain the species and sample responses by ordination axes that are linear combinations of environmental variables (Ter Braak, 1987). This results in an ordination diagramme known as a biplot, in which points represent species and sites, and vectors represent environmental gradients (Ter Braak, 1986). By connecting the origin of the plot (the centroid of the site points) with each of the arrow heads, the arrows representing the variables are obtained. The length of a vector representing each variable is a measure of how much the species distributions differ for that variable. The more important the variable, the longer the arrow. The ordination diagramme with environmental variable vectors, which determine a direction or axis, can be interpreted by extending the vector in both directions and dropping a perpendicular from each species point to this axis. The endpoints of the perpendicular indicate the relative positions of the centres of species distributions along the axis. The species endpoint which is furthest along the vector in the direction of the arrow has the strongest relationship with that specific variable (Ter Braak, 1986). The origin of the plot is the grand mean of each variable and the inferred weighted average is higher than the mean if the species endpoint lies on the same side of the origin as the head of an arrow, and is lower than average if the origin lies between the endpoint and the head of the arrow (Ter Braak, 1986).

RESULTS

Relationships between inflow and outflow and conditions within the impoundments

One-way analysis of variance (Zar, 1984) showed that the three sites at the receiving end of Arieskraal were not significantly different from each other for all variables measured and were thus assumed to be representative of the receiving end of the lake. A comparison of the surface water at the receiving end of each lake, Nuweberg Receiving (NR) or Arieskraal Receiving (AR) versus the corresponding inflowing water, respectively Nuweberg Inflow (NI) or Arieskraal Inflow (AI) showed no significant differences ($P < 0.05$) for Arieskraal. For Nuweberg the only significant differences were for TSS in summer and cyclopoid copepods and copepod nauplii during winter. A comparison of the bottom water at the outflowing end of each lake, Nuweberg Discharging (ND) and Arieskraal Discharging (AD)

Table 2: The means and standard deviations of the physico-chemical variables measured for all sites within the lakes, as well as the inflow to, and outflow from, each impoundment. Comparisons: inflow and the surface at the receiving end of Nuweberg (*) and Arieskraal (#), and the outflow and the bottom water at the discharging end of Nuweberg (underlined) and Arieskraal (bold)

	JANUARY 1988			JUNE 1988		
SITE	SURFACE	MIDDLE	BOTTOM	SURFACE	MIDDLE	BOTTOM
Temperature (°C)						
2	26.50 (0.50)*			10.47 (0.05)*		
NR	25.53 (0.21)*	24.33 (0.47)	22.07 (1.37)	11.03 (0.21)*	11.03 (0.21)	11.07 (0.31)
ND	23.93 (0.09)	19.83 (0.24)	18.50 (0.00)	11.07 (0.09)	10.00 (0.14)	9.57 (0.12)
3	18.50 (0.00)			9.50 (0.00)		
7	27.75 (0.75)#			12.37 (0.05)#		
AR	27.43 (1.17)#	20.33 (0.94)	16.83 (1.65)	12.67 (0.45)#	11.90 (0.14)	11.67 (0.05)
AD	24.17 (0.24)	16.73 (1.04)	**14.33 (0.47)**	11.70 (0.00)	11.63 (0.05)	**11.60 (0.08)**
9	**15.25 (0.25)**			**11.50 (0.00)**		
pH						
2	4.70 (0.02)*			4.11 (0.02)*		
NR	4.46 (0.20)*	4.57 (0.28)	4.79 (0.09)	4.31 (0.08)*	4.32 (0.05)	4.43 (0.00)
ND	4.92 (0.04)	4.82 (0.02)	4.67 (0.02)	4.41 (0.04)	4.42 (0.03)	4.42 (0.06)
3	4.58 (0.02)			4.43 (0.03)		
7	7.07 (----)#			6.90 (0.04)#		
AR	7.27 (0.23)#	6.60 (0.08)	6.43 (0.31)	6.43 (0.40)#	6.78 (0.06)	6.06 (0.60)
AD	7.45 (0.07)	6.09 (0.31)	**5.97 (0.05)**	5.95 (0.04)	5.87 (0.03)	**5.77 (0.02)**
9	**7.08 (0.60)**			**6.17 (0.05)**		
Dissolved Oxygen (% saturation)						
2	89.42 (1.25)*			99.94 (0.08)*		
NR	95.00 (2.39)*	92.99 (2.29)	92.87 (2.59)	98.70 (0.99)*	98.79 (0.84)	98.19 (0.84)
ND	92.41 (1.55)	75.89 (7.38)	48.11 (2.79)	98.04 (1.20)	95.20 (0.92)	93.36 (0.54)
3	97.73 (0.57)			100.59 (0.41)		
7	105.26 (----)#			100.92 (0.99)#		
AR	92.55 (3.32)#	63.86 (10.19)	24.08 (8.96)	100.47 (0.38)#	99.85 (0.21)	97.60 (0.55)
AD	87.17 (0.53)	8.17 (1.95)	**4.60 (1.03)**	99.24 (0.78)	96.96 (0.20)	**88.47 (7.42)**
9	**87.18 (0.00)**			**100.61 (0.43)**		
Conductivity ($\mu S\ cm^{-1}$)						
2	39.65 (0.60)*			39.30 (4.88)*		
NR	34.03 (0.41)*	34.87 (0.90)	35.97 (2.01)	41.20 (2.90)*	46.03 (2.05)	41.60 (2.87)
ND	37.30 (3.47)	40.80 (1.84)	37.70 (0.49)	53.50 (0.22)	54.00 (0.62)	52.37 (0.50)
3	34.40 (0.40)			51.77 (0.42)		
7	100.75 (2.85)#					
AR	91.27 (0.68)#	90.73 (0.54)	90.80 (3.51)			
AD	90.87 (0.31)	91.97 (3.15)	**101.97 (18.81)**	97.13 (1.09)	97.90 (0.41)	**95.60 (2.20)**
9	**86.40 (0.20)**			**88.03 (3.81)**		
Total Dissolved Solids						
2	42.13 (6.88)*			41.26 (1.51)*		
NR	37.67 (1.23)*	40.75 (1.62)	37.75 (4.32)	37.88 (6.63)*	33.38 (10.38)	43.00 (3.75)
ND	28.42 (4.18)	33.67 (6.15)	37.2 (50.74)	31.13 (8.63)	40.67 (4.38)	38.83 (3.79)
3	35.75 (1.25)			40.33 (1.70)		
7	76.38 (5.13)#			56.75 (4.80)#		
AR	81.58 (2.59)#	78.83 (2.28)	59.33 (17.03)	68.42 (4.86)#	67.00 (6.34)	70.0 (10.01)
AD	67.75 (2.13)	85.32 (3.27)	**80.9 (24.44)**	62.25 (8.10)	63.25 (12.01)	**52.50 (5.31)**
9	**60.13 (1.88)**			**65.67 (8.96)**		
Total Suspended Solids						
2	0.82 (0.12)*			0.53 (0.22)*		
NR	3.10 (0.20)*	2.15 (0.29)	2.67 (0.31)	2.18 (0.44)*	2.31 (0.87)	2.71 (0.66)
ND	2.98 (0.39)	1.69 (1.20)	2.62 (0.17)	2.00 (0.11)	1.60 (0.11)	1.47 (0.29)
3	2.87 (0.54)			2.53 (1.80)		
7	2.54 (0.06)#			6.44 (1.16)#		
AR	1.49 (0.64)#	2.59 (1.27)	2.47 (1.20)	5.28 (0.34)#	6.44 (0.97)	8.72 (5.63)
AD	2.24 (0.97)	3.10 (0.89)	**1.96 (1.05)**	6.06 (0.82)	5.37 (1.53)	**16.33 (13.91)**
9	**2.24 (0.24)**			**7.67 (0.62)**		

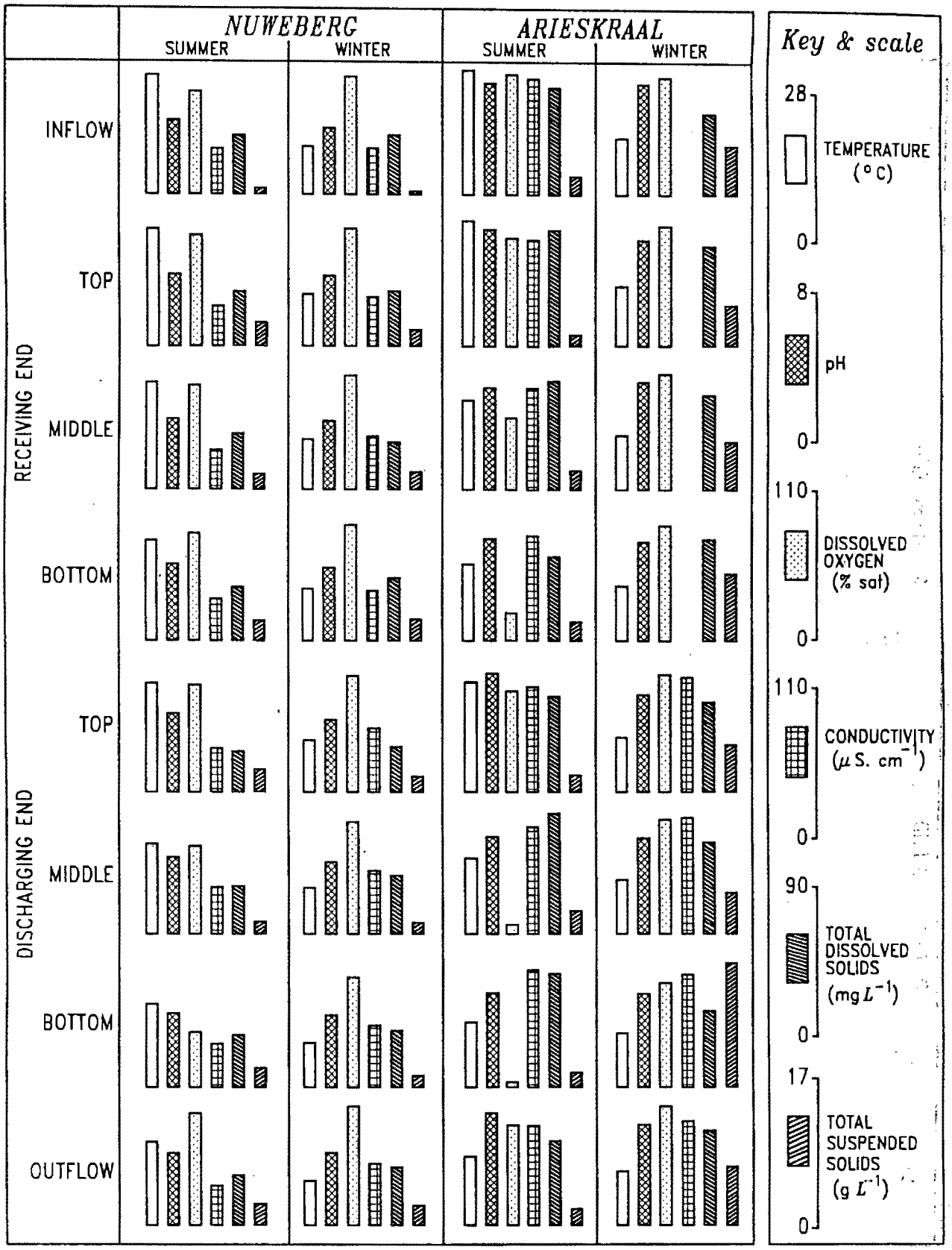


Figure 2: Bar-graph comparisons of the various physico-chemical parameters measured for all sites within the lakes as well as the stream sites upstream (inflow) and downstream (outflow) of each impoundment. Note that the scale of the bar is different for each variable and is given in the key.

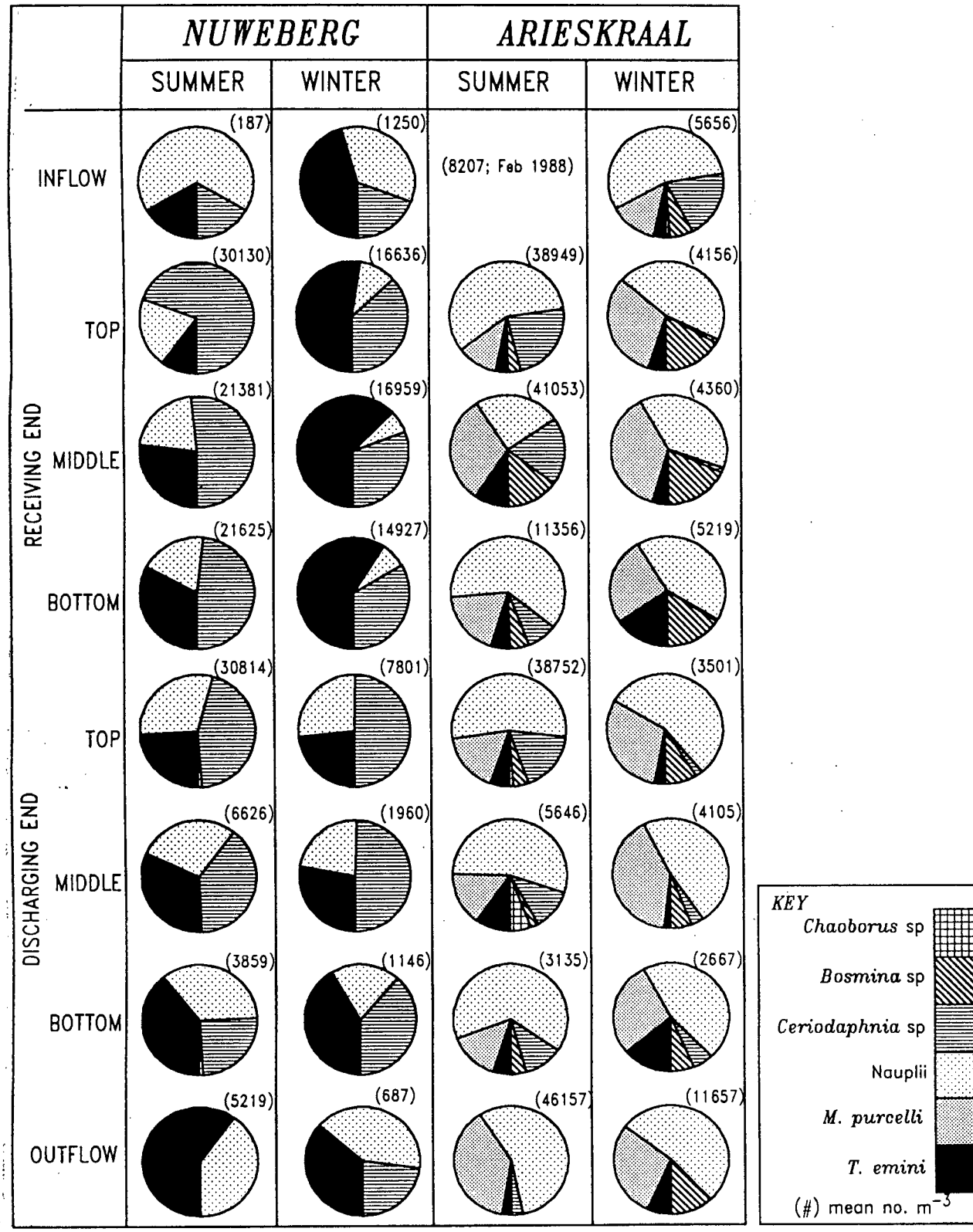


Figure 3: Community structure pie diagrams for the various sites within the dams, as well as for the upstream (inflow) and downstream (outflow) sites.

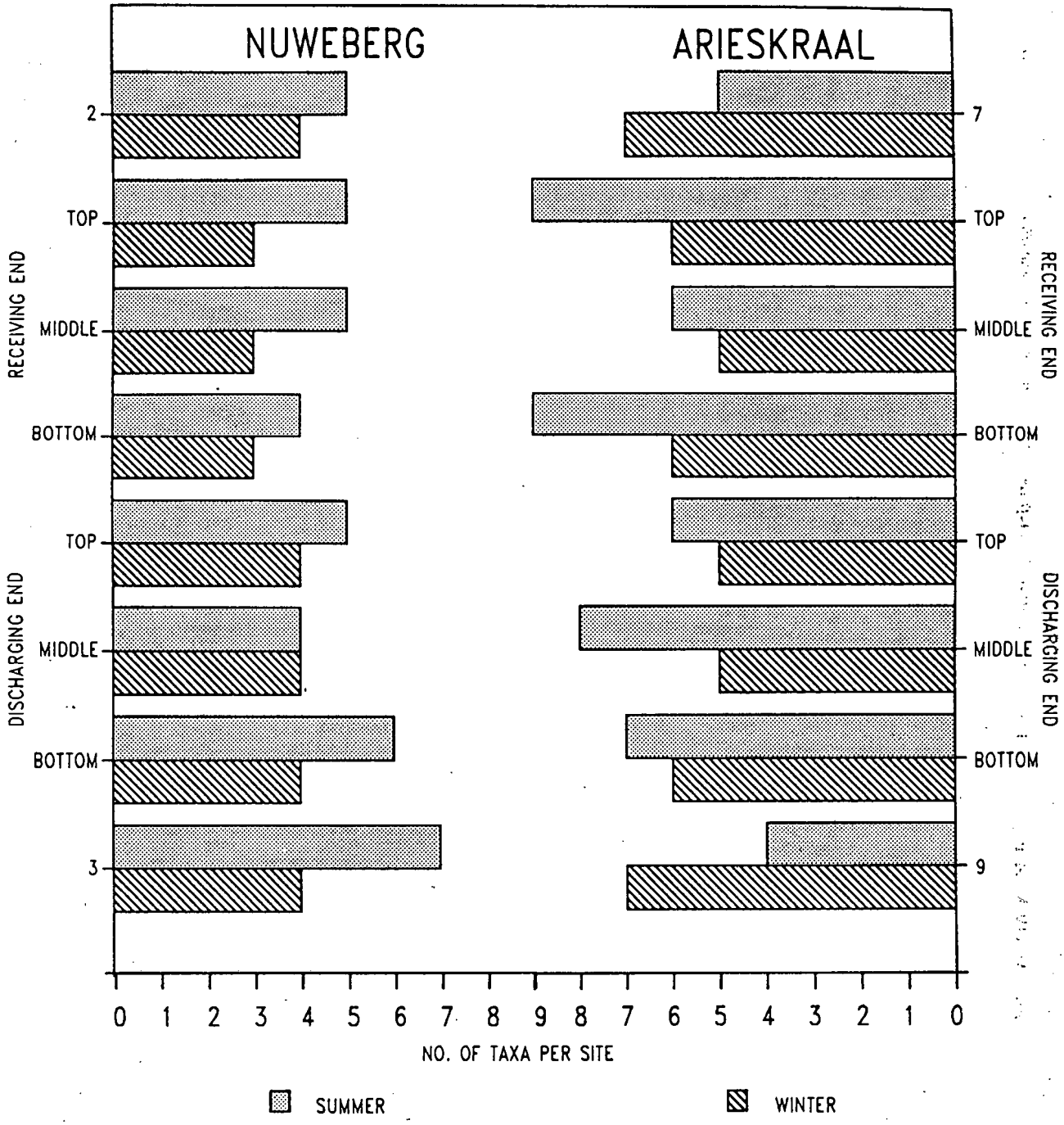


Figure 4: Taxonomic richness (i.e. number of taxa per site) in summer and winter for the various sites within the each dam, as well as for the upstream (inflow) and downstream (outflow) sites.

Table 3: Significance levels for ANOVA analysis for differences between depths, sites dams and seasons. *=p<0.05; ns=not significant; space=no sample.

	temperature		pH		oxygen		Conductivity		TDS		TSS		Cyclopoids		Calanoids		nauplii		*Ceriodaphnia*		*Bosmina*		Chaoboridae	
	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W
NR:ND	ns	*	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	*	ns	ns	ns	ns
NR:AR	ns	*	*	*	ns	ns	*		*	*	ns	ns	*	*	*	*	ns	ns	ns	*	ns	*	ns	ns
NR:AD	*	*	*	*	*	ns	*	*	*	*	ns	ns	*	*	ns	*	ns	ns	ns	*	ns	ns	*	ns
ND:AR	ns	*	*	*	ns	ns	*		*	*	ns	ns	ns	ns	*	*	ns	ns	ns	ns	ns	*	ns	ns
ND:AD	ns	*	*	*	*	ns	*	*	*	*	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	*	ns
AR:AD	ns	ns	ns	*	ns	ns	ns		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
NR																								
TOP:MID	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TOP:BOT	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MID:BOT	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
ND																								
TOP:MID	*	*	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	*	*	ns	ns	ns	ns
TOP:BOT	*	*	*	ns	*	*	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	*	*	*	ns	ns	ns	ns
MID:BOT	*	*	*	ns	*	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
AR																								
TOP:MID	*	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TOP:BOT	*	*	*	ns	*	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MID:BOT	ns	ns	ns	ns	*	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
AD																								
TOP:MID	*	ns	*	ns	*	ns	ns	ns	ns	ns	ns	ns	*	ns	*	ns	*	ns	*	ns	ns	ns	ns	ns
TOP:BOT	*	*	*	ns	*	ns	ns	ns	ns	ns	ns	ns	*	ns	*	ns	*	ns	*	ns	ns	ns	*	ns
MID:BOT	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns

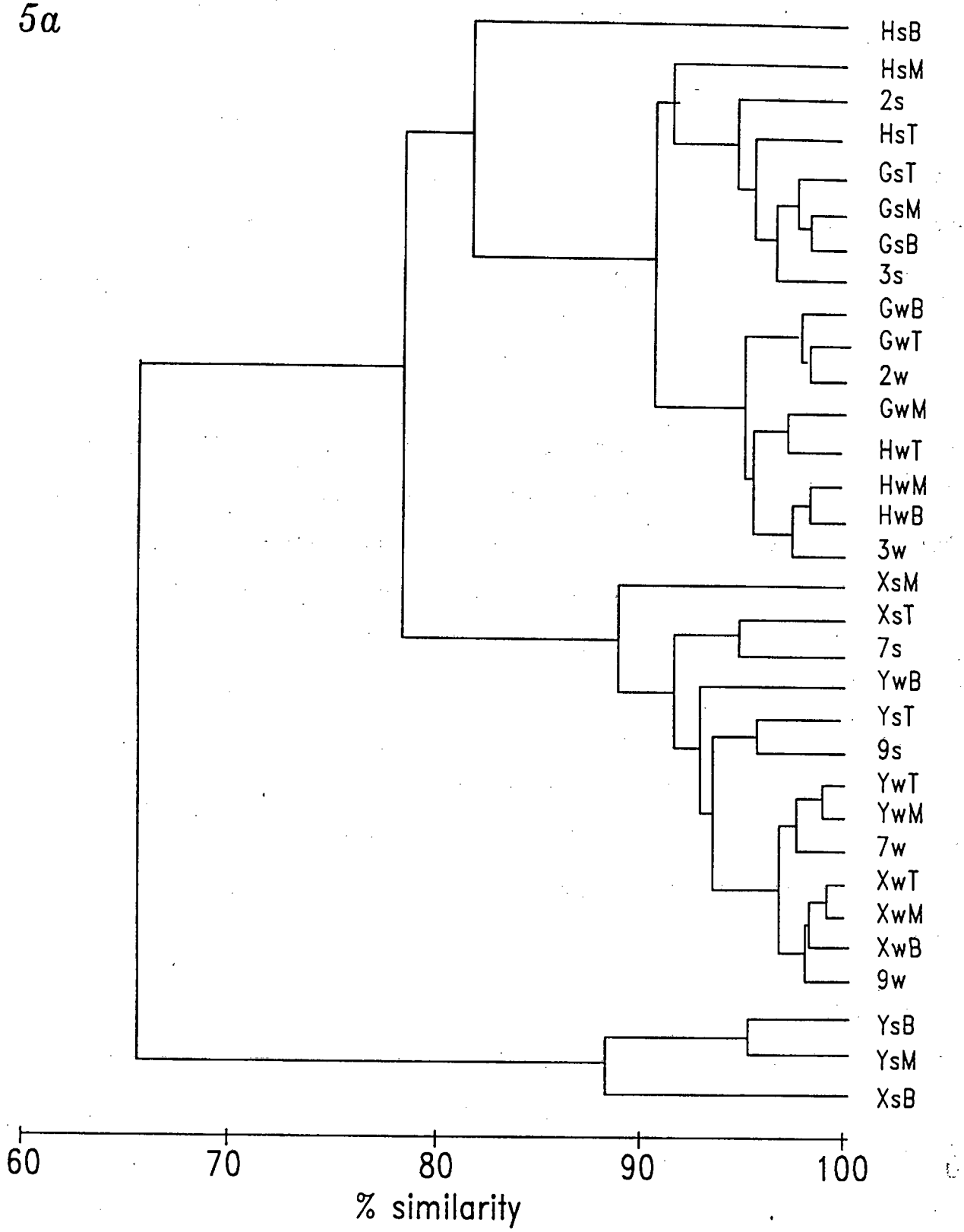


Figure 5a: Dendrogram of the Bray-Curtis similarity between sites using all the physico-chemical data collected. G = Nuweberg receiving end, H = Nuweberg discharging end, X = Arieskraal Receiving end, Y = Arieskraal discharging end, T = Top, M = Middle, B = Bottom, s = Summer, w = Winter, and 2, 3, 7, 9 = river sites PR2, PR3, PR7, PR9 respectively.

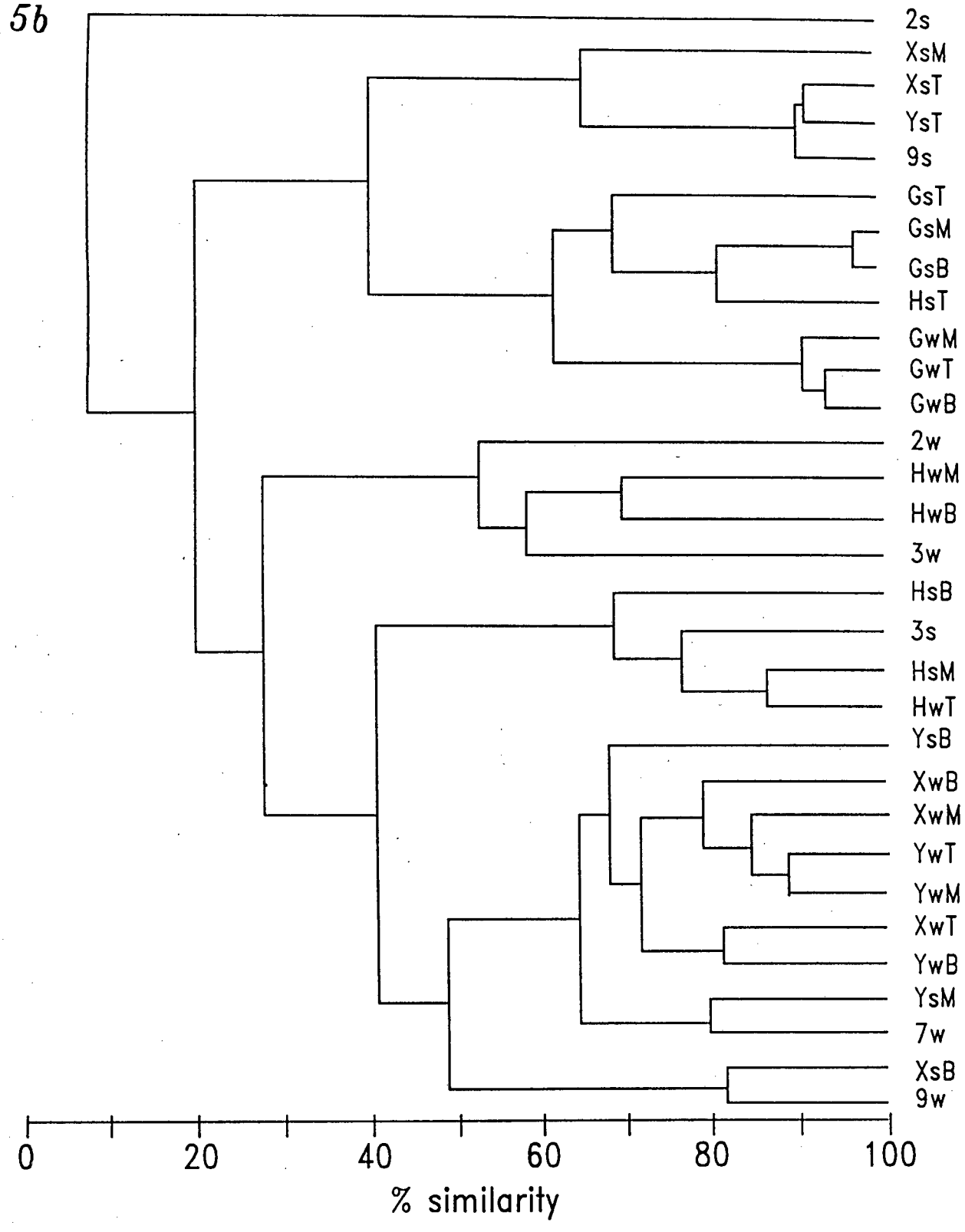
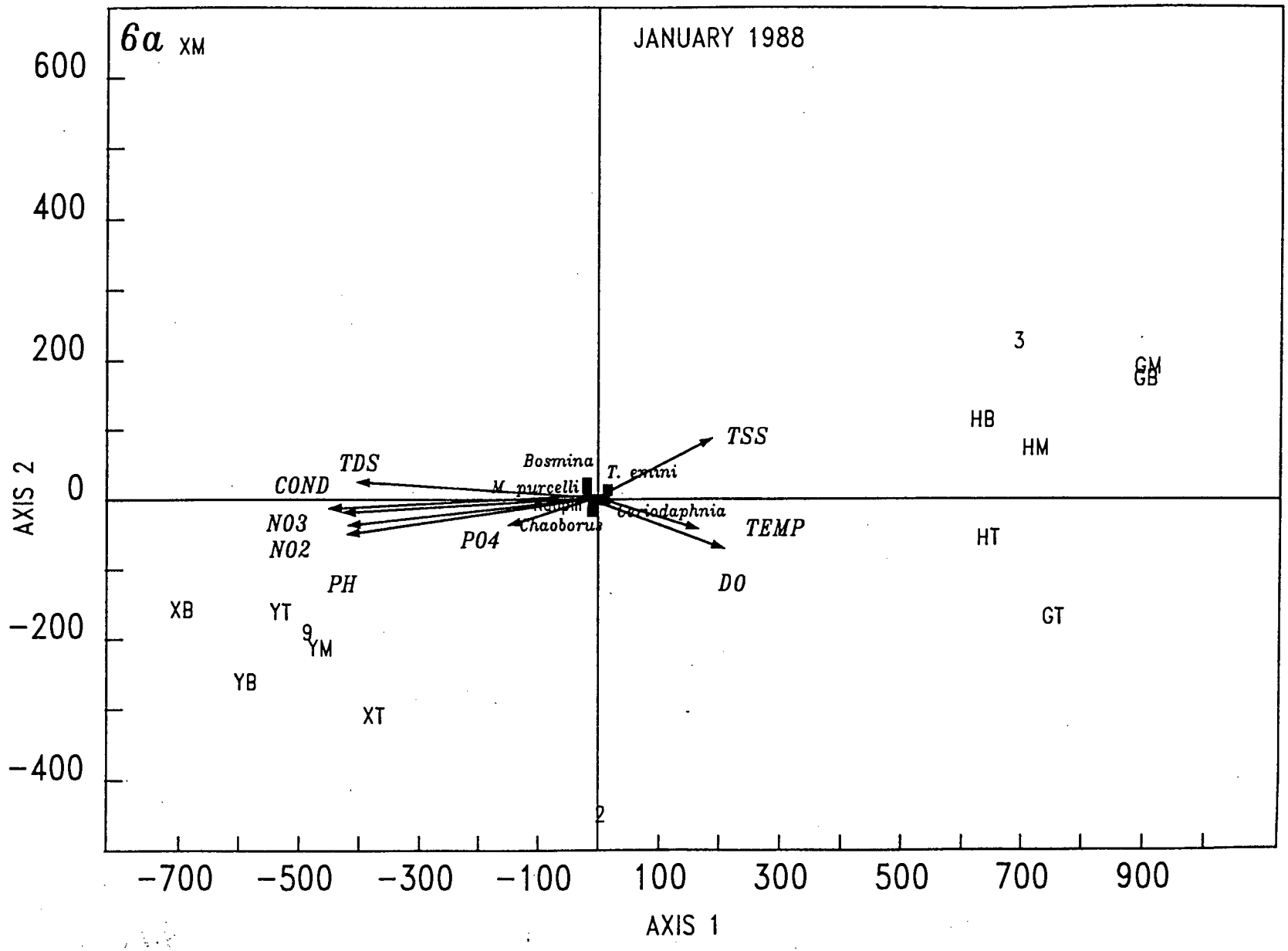


Figure 5b: Dendrogram of the Bray-Curtis similarity between sites using all the biological data collected. G = Nuweberg receiving end, H = Nuweberg discharging, X = Arieskraal Receiving, Y = Arieskraal discharging, T = Top, M = Middle, B = Bottom, s = Summer, w = Winter, and 2, 3, 7, 9 = river sites PR2, PR3, PR7, PR9 respectively.


6a XM
JANUARY 1988
600
400
200
0
−200
−400
AXIS 2
−700
−500
−300
−100
100
300
500
700
900
AXIS 1
TDS
COND
NO3
NO2
PH
PO4
TSS
TEMP
DO
Bosmina
M. purcelli
T. emini
Chaoborus
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GB
3
9
2

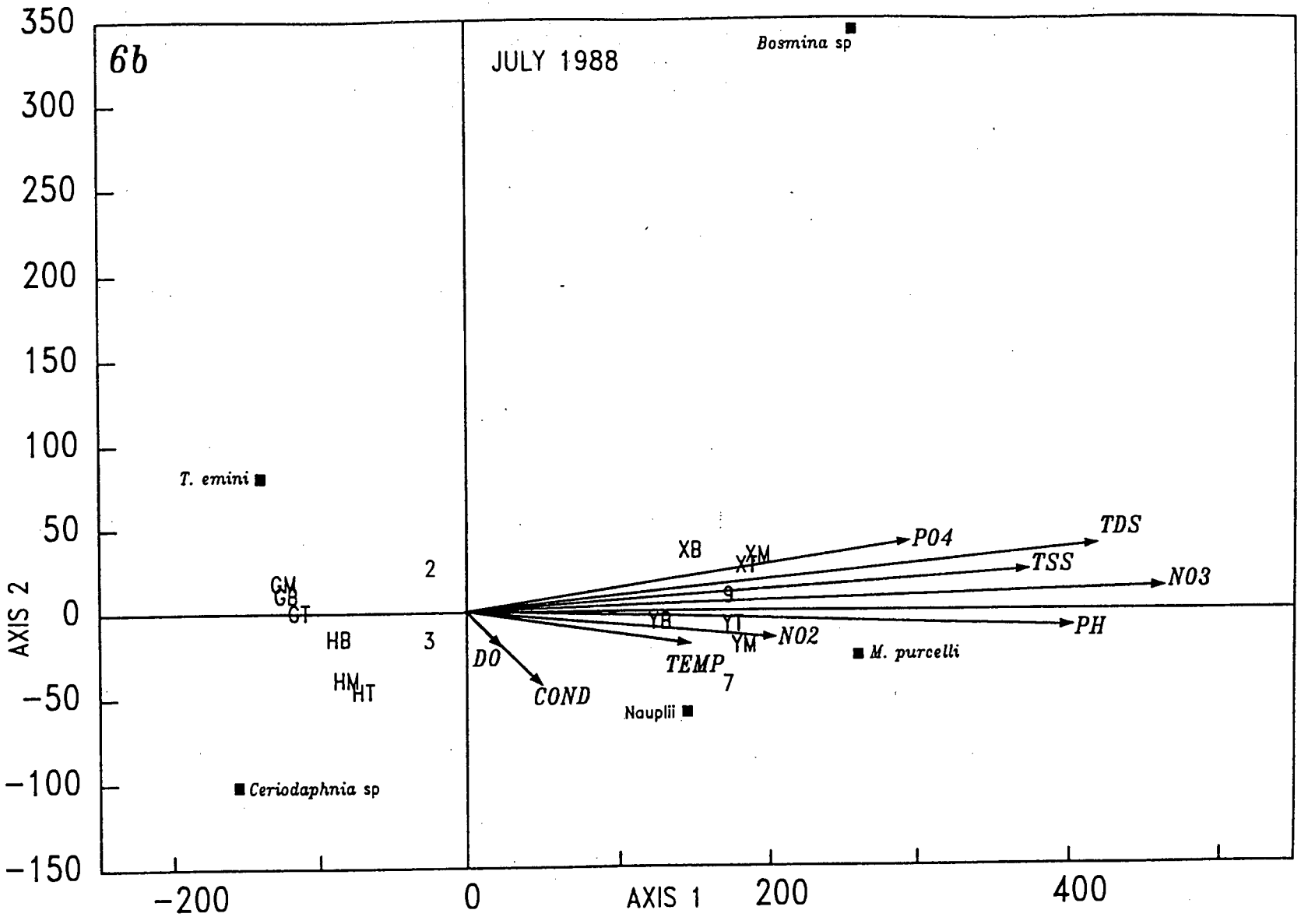

Figure 6: Canonical correspondence analysis of the lakes biological data compared with the environmental gradients for a) January 1988 and b) July 1988. (G = Nuweberg receiving end, H = Nuweberg discharging, X = Arieskraal Receiving, Y = Arieskraal discharging, T = Top, M = Middle, B = Bottom, s = Summer, w = Winter, and 2, 3, 7, 9 = river sites PR2, PR3, PR7, PR9 respectively.)

The cluster of all the physico-chemical variables (Figure 5a) shows a 65% similarity of all sites, with a split at that point of three of the Arieskraal summer sites (XsB, YsM & YsB) from the rest. The remaining sites then split, at the 78% similarity level, into two distinct groups, Nuweberg and Arieskraal. Within these groups Nuweberg splits almost perfectly into summer (Gs or Hs) and winter groups (Gw or Hw), except for the summer bottom sample at the discharging end (HsB) which splits off from all the rest at around 80% similarity. The Arieskraal winter samples form a distinct group, but the discharging samples relate more closely to the inflow water and the receiving samples to the outflow water. At approximately the 95% similarity level there is definite distinction between sites from different seasons. The cluster of the faunal samples (Figure 5b) shows groupings of Nuweberg and Arieskraal samples interspersed with each other as well as a few groups of Arieskraal linked with Nuweberg samples. There is only a 10% similarity of the Nuweberg inflow (site 2) to the rest. At the 30% similarity level two groups emerge but no definite distinction between lakes or seasons. Only at a higher percentage similarity do groups occur which are either Nuweberg or Arieskraal, but there is also some inter-mixing. In the dendrograms and other clustering diagrams produced (Figures 5 & 6), the following codes for sites were used:

Correspondence Analysis

Canonical Correspondence Analysis (CCA) of the lake data, using CANOCO, highlights the distinctions between the two impoundments and relates them to the environmental variables. Separate summer and winter data sets (Figures 6a & 6b respectively) show a good relationship between site ordination and environmental gradients. The January data (Figure 6a) shows the Arieskraal sites (X's, Y's and 9) grouped around the environmental variables that showed higher values in Arieskraal than in Nuweberg (Table 2 and Figure 2). Due to an error during sample processing no summer data are available for site 7. The Nuweberg sites (G's, H's, 2 and 3) are grouped on the side of Axis 1 where the environmental variables show little distinction between lakes but where Nuweberg showed slightly higher values (weak gradients) (Table 2 and Figure 2). The outflow from Arieskraal (site 9) ordinates close to the samples from the discharging end of Arieskraal (Y's); the outflow from Nuweberg (site 3) groups closely to all Nuweberg sites (G's & H's) and is situated quite close to the bottom sample from the discharging end of Nuweberg (HB). The inflow

to Nuweberg (2) separates from all the other sites and is situated at the zero point of Axis 1. The zooplankton species ordinate very close to the centre (Figure 6a). Species that only occur in Arieskraal (*M. purcelli* and *Bosmina* sp) as well as those that are predominant in the surface waters (mainly in Arieskraal viz. copepod nauplii and *Chaoborus* sp; see Figure 3) are situated on the Arieskraal side of Axis 1 (Figure 6a), whereas those species that predominate in Nuweberg (*T. emini* and *Ceriodaphnia* sp; see Figure 3) occur on the Nuweberg side of Axis 1 (Figure 6a).

The analysis for July (Figure 6b) shows distinct grouping of the Arieskraal sites to the right and Nuweberg to the left of Axis 1. The receiving sites are positioned above 0 and the discharging sites below 0 on Axis 2: i.e. the ordination diagramme divides neatly into four quadrants except for the inflow and outflow from Arieskraal (7 & 9) which ordinate closest to the sites at the opposite ends of the lake (Y's & X's respectively). In winter all environmental variables show higher values in Arieskraal than in Nuweberg (Table 2 and Figure 2) and thus all environmental gradients extend into the Arieskraal side of Axis 1 (Figure 6b). DO, the shortest vector, shows very little difference between the two impoundments. Once again, the species that predominate in Arieskraal occur on the Arieskraal side of Axis 1 and likewise for Nuweberg (Figure 6b). In both summer and winter (Figures 6a & b) *M. purcelli* and *Bosmina* sp occur closer to, and on the same side of Axis 1 as the head of the pH vector, than the species that are dominant in Nuweberg.

DISCUSSION

Relationships between sites and depths

The differences in water chemistry between the two impoundments are also evident in the inflow to and outflow from each impoundment (Table 2 and Figure 2) and indicates changes in the chemical composition of the water as the river flows from upper to middle reaches. This alteration in chemical environment is due to the geology and land-use patterns surrounding the two reaches: the upper reach drains predominantly fynbos-covered sandstones (Figure 1) resulting in low pH and low ionic content; the middle reaches drain

shales (Figure 1) extensively used for fruit farming which result in a higher pH and ionic content.

The impoundments exhibit a warm monomictic pattern and seasonality is evident in both lakes with typical summer layering and winter mixing (e.g reviews by Hutchinson, 1957 and Wetzel, 1982). The differences between layers is more pronounced in the larger lake, Arieskraal, as shown also in the ANOVA analysis (Table 3). Egborge (1979) commented that the pattern of stratifications in pH, alkalinity, conductivity and phosphate, in his study on Lake Asejire, Oyo State, Nigeria, were generally in phase with thermal stratification. According to Denny (1972) a positive correlation between thermal and chemical stratification is possible in stable water bodies. Stratification is important with respect to the water released from reservoirs as the degree of stratification will influence the quality of the water released. A high degree of temperature stratification will result in an increase in the temperature of the receiving stream from a top-release dam and a decrease in temperature from a bottom-release dam. Oxygen stratification, with very low concentrations of dissolved oxygen in the bottom layer could result in the release of oxygen deficient water from a bottom-release reservoir with resultant adverse effects on the downstream biota. The high degree of dissolved oxygen stratification in summer, especially in Arieskraal, with close to anoxic conditions at the bottom of the discharging end (Table 2 and Figure 2), is not evident in the outflow (site 9), however. This is evidence of sufficient re-aeration during passage through the outlet works (Hannan and Young, 1972; Novotny 1985). The outflow pipe for Arieskraal is situated approximately 2 m above the stream bed and sprays the water over a distance of 5 m. The outflow pipe at Nuweberg is also well designed for re-oxygenation, with a large pipe approximately 5 m above the stream bed spraying a broad stream of water above a pool which itself was probably created by the continuous, relatively high velocity of the flow. This flow is greatest during summer, when water is released for irrigation storage and abstraction further downstream (Byren and Davies, 1989).

Very few differences were found between the inflow *versus* the surface samples at the receiving ends, and between the outflow *versus* the bottom water at the discharging ends of the lakes. However, these differences may be attributed to factors such as lake circulation patterns (eg. density currents: Imberger *et al.*, 1978; Hamblin and Carmack, 1980;

Imberger and Patterson, 1981; Imberger and Hamblin, 1982; Patterson *et al.*, 1984) or localised pockets of water (Fischer and Smith, 1983). The general increase in nutrients and decrease in temperature from inflow to outflow of an impoundment (also noted in Rada and Wright 1979; Byren and Davies, 1989) is evidence of cold, nutrient rich water being discharged into the stream (Ward, 1974). Hypolimnal release reservoirs, in contrast to natural lakes, are thus termed "heat traps" and "nutrient exporters" (Odum, 1971).

Zooplankton community structure

The difference in zooplankton community structure between the two lakes is the result of different chemical environments (as explained above). The absence of *M. purcelli* and *Bosmina* sp in Nuweberg is possibly pH related as indicated by the close proximity of the endpoints of these species to the head of the pH vector in the CANOCO plots (Figure 6a & b). Hutchinson *et al.* (1932) found *M. purcelli* in reservoirs with a pH of 5.2 - 6.1, and from the work by Hutchinson *et al.* (1932) and Gardiner (1988) *M. purcelli* appears to be common in humic waters with low salinities. Although the humic acid content of the Palmiet River water was not measured, the dark brown colour of the water is indicative of the presence of humic substances (Gardiner, 1988) which has been confirmed by a recent study by Koch *et al.*, (in press).

The lower numbers of zooplankton recorded in the bottom-layer samples, except at the receiving end of Nuweberg, which is very shallow (2.5 to 3 m), could be the result of stratification. The reduction in temperature, dissolved oxygen and light penetration, even at these comparatively shallow depths (15 m to 18 m), are enough to discourage extensive habitation by zooplankton. The copepods and *Bosmina* sp showed highest densities in the middle samples of most sites which may be the result of daily migrations within the water column. Coetzee (1976) recorded highest densities of zooplankton in the Wilderness Lakes, South Africa, at 4 m and Wetzel (1982) noted that one of the most conspicuous features of the cladoceran zooplankton, and to a lesser extent of copepods, was marked vertical migration. Most species migrate from deeper waters to the surface as darkness approaches and return to deeper strata at dawn (Wetzel, 1982). The responses to light changes are conspicuous, but there is no evidence to suggest that the zooplankton is attempting to remain in a constant photoenvironment (Wetzel, 1982). In some species reverse migration can

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SYNTHESIS

Stream regulation has profoundly influenced virtually all of the world's major river systems (Ward & Stanford, 1979). The most obvious environmental changes induced by impoundment of a river occur behind the wall, where a lotic environment is transformed into a lentic environment (Ward, 1982). However, the structure and functioning of the remaining lotic reaches are also greatly modified by stream regulation (Ward, 1982).

This thesis discusses separately several factors affected by stream regulation. The environmental conditions in the lotic reaches below impoundments are a function of 1) the quality of water entering the reservoir (Papers I & II); 2) the limnological phenomena within the reservoir (Paper V) and 3) the operational variables at the dam. The interaction of physical and chemical factors (Papers I and II) as well as the characteristics of invertebrate drift (Paper III), will profoundly influence stream benthos (Paper IV).

1) Does the Palmiet River conform to the predictions of the RCC and SDC?

The answer to the question is given in Figure 1, which shows the comparison between the predictions of the RCC (solid line) and the SDC (dot-dash line) with the conditions in the Palmiet River (bold dashed line) for the variables tested in this project. Although the RCC and SDC do not provide actual values for the x and y axes, for comparative purposes the trends hypothesised in the RCC, as interpreted by Ward and Stanford (1983), and the SDC have been superimposed on the results obtained for the Palmiet River. We see that the Palmiet River conforms to the predictions of the RCC and SDC for certain variables and in some sections of the river.

CPOM:FPOM ratio: The RCC (Vannote *et al.*, 1980) predicts that the ratio of CPOM:FPOM will decrease as stream order increases (ignoring the very small headwater streams, which lack the power to move even small particles, thus having a very low ratio of CPOM:FPOM: Cummins, 1975, 1977). In the Palmiet River the ratio of transported CPOM:FPOM is low in the headwaters (4 km from the source), increases slightly over the next 4 km and, ignoring the effect of the dams, appears to remain constant to the estuary (Figure 1a). Results from the Palmiet river thus support the conclusion of Naiman and Sedell (1979) that stream order alone is not a good indicator of CPOM:FPOM ratios. The

SDC predicts that the ratio of CPOM:FPOM will decrease below both an upper- and a middle-reach impoundment, the decrease being more marked below the upper-reach impoundment. The effect of impoundments on the Palmiet River compares well with the predictions of the SDC below the middle-reach impoundment, Arieskraal, but not so well directly below the upper reach impoundment, Nuweberg, mainly due to the fact that both CPOM and FPOM occur in extremely low quantities and thus even a small change in either will significantly affect the ratio. Quantities of CPOM are usually reduced below impoundments since instream transport from upper reaches is eliminated (Ward, 1976).

Annual temperature range: The SDC predicts little impact by upper-reach impoundments on annual temperature range, but major impacts by mid and low-reach structures. In the precipitous Palmiet, a distinct impact is caused by the upper-reach impoundment, Nuweberg, with no recovery before the next impoundment, while for the mid-reach impoundment, a major thermal impact is obvious due to hypolimnetic discharge (Figure 1b).

Plankton: The RCC also predicts that plankton levels will be low in the upper and middle reaches and increase steadily towards the mouth. In the Palmiet River zooplankton levels are very low throughout except immediately below the impoundments (Figure 1c). The SDC predicts that the plankton addition to the stream would be greater below the middle-reach as opposed to the upper-reach impoundment and that recovery below both impoundments would be rapid. However, the upper-reach impoundment on the Palmiet River introduced far larger numbers of zooplanktonic organisms into the river than the middle-reach impoundment did, although recovery below both was very rapid. This reversal in plankton response may be due to the differing release mechanisms of the two dams: Nuweberg discharges higher volumes of water in summer than in winter as it is a holding reservoir for an irrigation supply reservoir further downstream, whereas Arieskraal discharges a more or less constant volume throughout the year.

Biotic diversity: Biotic diversity is not defined in the SDC and is interpreted here as both drift taxonomic richness and benthic taxonomic richness and as benthic Shannon diversity (Figure 1d). The RCC predicts maximum biotic diversity in the middle reaches of a river, whereas in the Palmiet River, maximum taxonomic richness occurs in the upper reaches and

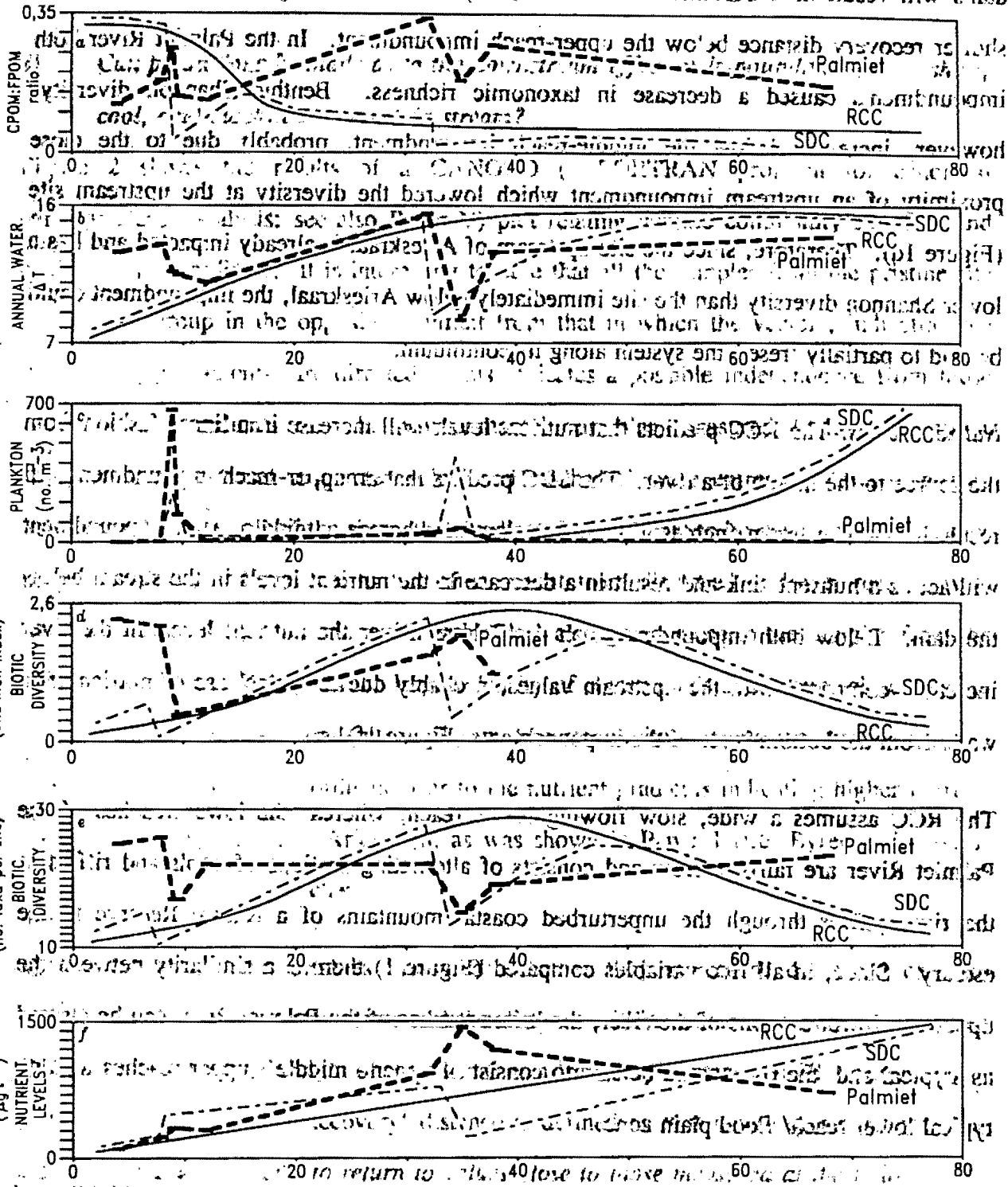

Figure 1: A comparison between the predictions of the RCC (solid line) and the SDC (dot-dash line) with the conditions in the Palmiet River (bold dashed line) for the variables tested in this project. Note that since the SDC does not define biotic diversity, it is shown here both as Shannon diversity in the benthos (d) and taxonomic richness in the drift (e).

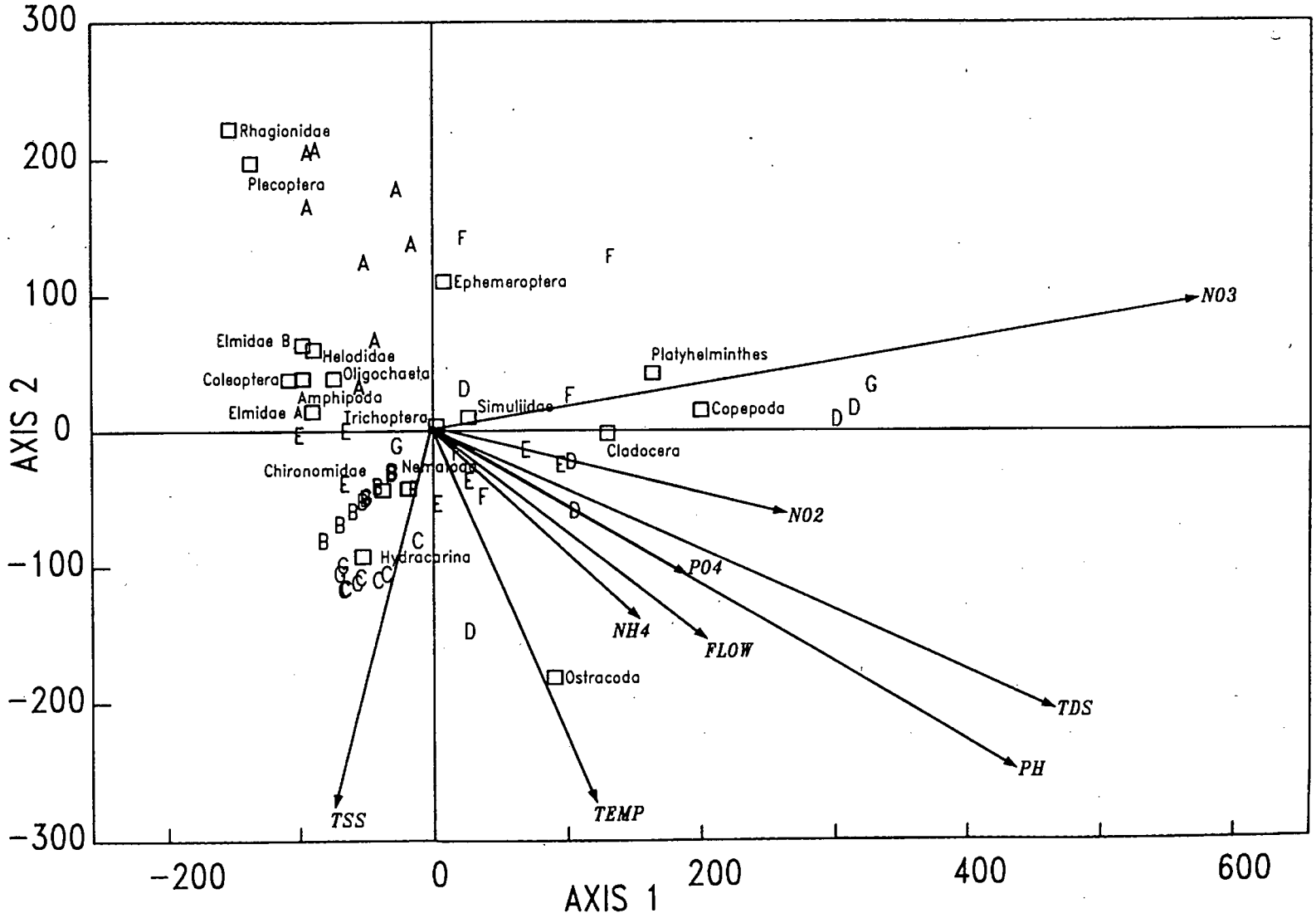

Figure 2: The results of using CANOCO (a FORTRAN program for canonical correspondence analysis) to relate benthic community structure and environmental gradients. (A=PR1; B=PR2; C=PR4; D=PR7; E=PR8; F=PR9; G=PR10)

Table 1: All the variables measured and whether they increased, decreased or were unchanged below the impoundments and the distance within which recovery occurres as a percentage of the overall length of the river (i.e a 'recovery' distance of 30 km in a 74 km long river equals 40%). A recovery distance of 40% below Arieskraal represents a recovery just before entering the estuary.

VARIABLE	NUWEBERG	ARIESKRAAL
Flow volume	↑ >4%	↓ 4%
Temperature	↑ (4%)	↓ (40%)
Annual Δ T	↓ >4%	↓ (40%)
pH	↑ 0.7%	↓ >40%
Alkalinity	↑ 4%	↓ >40%
Conductivity/TDS		
Nitrite	↑ >4%	↑ 4%
Nitrate	↑ 0.7%	↑ 4%
Ammonium	↑ 4%	↑ 40%
Phosphate	↓ >4%	↑ 4%
TSS	↑ >4%	↑ 40%
CPM	↓ (4%)	↓ 40%
FPM	↓ 4%	↓ 40%
VPM	↓ 4%	↓ 40%
UPM	↑ (4%)	↑ 40%
CPOM	↓ 4%	↓ 40%
FPOM	↓ 4%	↓ 40%
VPOM	↓ (4%)	↑ 40%
UPOM	↑ (4%)	↑ 40%
CPIM	↓ 4%	↓ 40%
FPIM	↓ 4%	↓ 40%
VPIM	↓ 4%	↑ 40%
UPIM	↑ (4%)	↑ 40%
%CPOM	↑ 4%	↑ 40%
%FPOM	↓ (4%)	↑ 40%
%VPOM	↓ (4%)	↑ 40%
%UPOM	↓ >4%	↓ 40%
CPOM:FPOM	↑ >4%	↓ 40%
Drift density	↑ 4%	↑ 4%
Drift biomass	↑ 4%	↑ 4%
Drift taxon richness	↓ (4%)	↓ 40%
Benthic density	↑ >4%	↑ 4%
Benthic taxon richness	↓ >4%	↓ (4%)
Benthic diversity	↓ >4%	↑ 40%

the more shallow gradient of the river and the added disturbance due to fruit farming activities along the first 8 km below the impoundment. The distance over which recovery can take place is, however, sufficiently long to allow most variables to reset before the river enters the estuary.

Figure 3 is a stylised representation of the factors that affect conditions within a river, how an impoundment influences the river and the factors that may influence the length of the recovery distance. A feedback loop for multiple impoundments is also included.

From Figures 1, 2 and 3 and Table 1 presented, it is obvious that the alterations to the functioning of a river system as a result of impoundment are many and varied. Predictions are therefore not easy. It is concluded that a western-Cape, acid blackwater stream conforms to some, but not all, of the predictions of the RCC and SDC. Recovery distances appear to be shorter or non-existent below the upper reach impoundment owing to the size and release patterns of the impoundments as well as to the steep gradient and pristine condition of the reach immediately below the impoundment. Unfortunately the distance available over which reset can take place is only about 7 km before the river flows into the next impoundment on the system, and thus some variables do not reset at all. The Palmiet system is therefore not ideal for answering all the questions: recovery might have occurred below Nuweberg if the distance to the next impoundment had been longer; the interpretation of recovery below Arieskraal may have been different if the upstream section had not been disturbed by the close proximity of another impoundment. This has however, highlighted an important issue: the hypotheses tested make several assumptions with respect to other perturbations in the system and in this day and age with the rapidly expanding global human population a natural, unperturbed river may be extremely difficult to find. Hypotheses which take into account the various different types of perturbations that can occur in/on/around a river system would be of great value. It is hoped that the results from the present study, along with those from the sister project on the Buffalo River, eastern Cape, South Africa, and including other similar studies (e.g Zeiser, 1985) may be used to develop such hypotheses and/or predictive mathematical models.

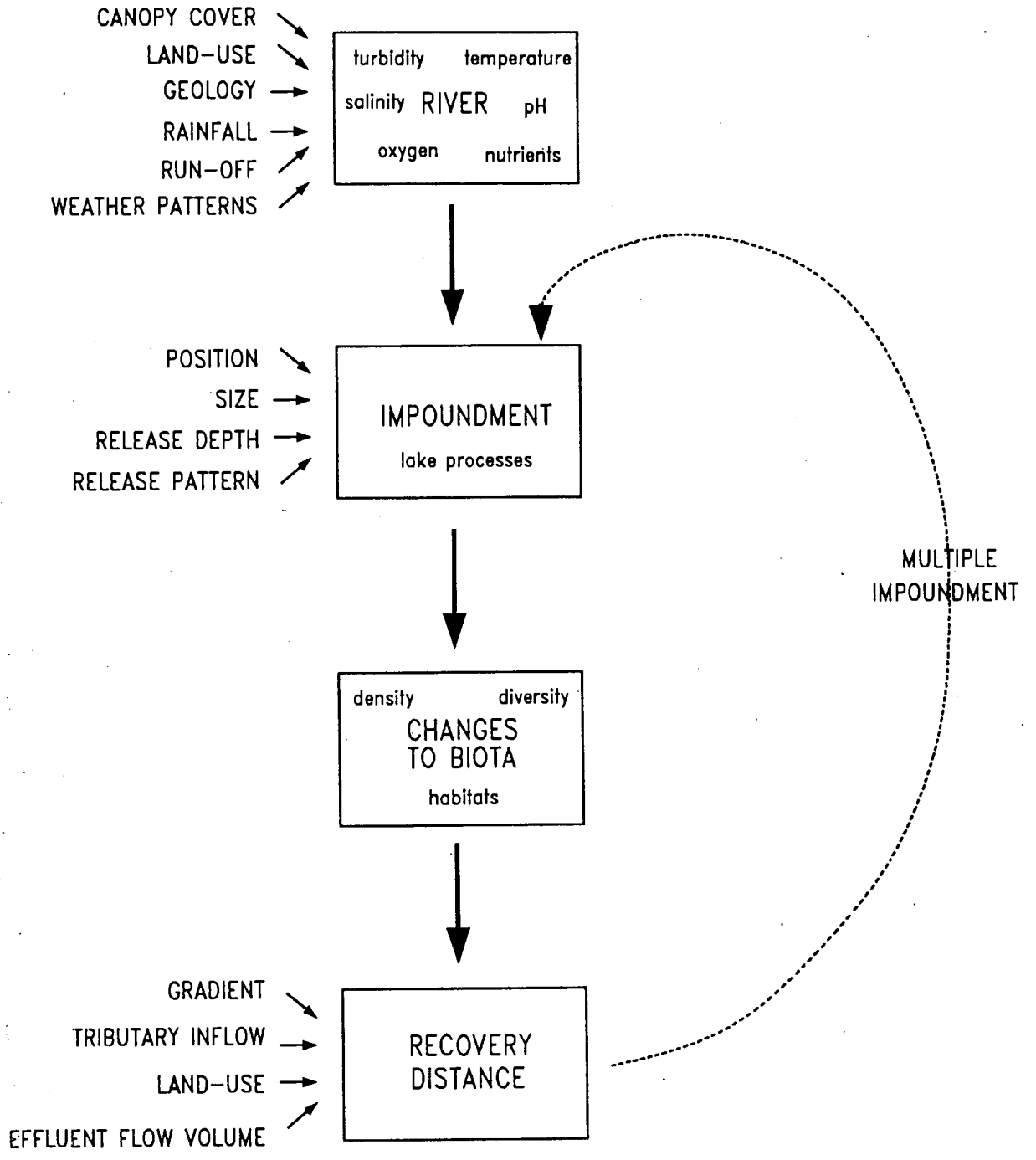

Figure 3: A stylised representation of the factors that affect conditions within a river, how an impoundment influences the river and possible factors that influence the length of the recovery distance. A feedback loop for multiple impoundments is also included.

Management implications and recommendations for river regulation

The manager of the release from an impoundment can have a maximum of only two operational variables under his direct and immediate control: discharge and release depth. Release depth influences such factors as nutrients, seston, dissolved oxygen, toxins and the temperature of water discharged from the impoundment. Control of the flow regime can have a wide range of effects (Ward 1982). For instance, an increase in current velocity could decrease the recovery distance for nutrient concentrations but increase the recovery distance for temperature, carrying the cold, bottom-release water faster and hence further downstream. A more constant current velocity and discharge could create a favourable climate for certain species, often pest species such as blackfly, caddisfly and chironomid midge larvae and undesirable noxious weeds such as e.g *Myriophyllum aquaticum* ('parrots feather').

Dams with selective depth withdrawal capabilities may be used to meet managerial objectives (e.g. maintenance of river ecosystem functioning) providing that the relevant information on the needs of the ecosystem is available. A fuller understanding of the ecological ramifications of various operational schemes was identified as a research need by Ward (1982), and is still necessary if conditions in the receiving stream environments are to be optimised.

All proposals for dam construction should include an environmental impact assessment which includes a record of the natural riverine conditions prior to impoundment. Should the proposed impoundment be deep enough for the establishment of a thermocline and for the stratification of various physical and chemical parameters to occur, the wall should include multi-level draw off facilities so that the operator can release water that will mimic the riverine conditions prior to impoundment.

The construction of a dam can have far reaching environmental effects as a result of short-term planning procedures adopted because of technological, economic or merely political demands (Petts, 1980). The aim of environmental management should be to optimize development and resource-use by minimising both costs and impacts (Clark, 1978). Many decision makers still expect the environment to respond in a simple linear manner to an applied stress, and only perceive the immediate short-term consequences, with little

understanding of the dynamic nature of the environment, and of the long time required for environmental readjustment in response to human impact. Many decision makers also expect there to be a neat "threshold" of response to disturbance: the present study shows clearly that thresholds are variable for different characteristics and may therefore be dangerous if used by managers. Moreover, an interdisciplinary approach should be adopted within the long-term perspective (Petts, 1980) for all water development projects. Thus, it will only be with due appreciation of the intricate composition of natural systems and a realisation of the delicate balance in which these systems are maintained, that the widespread present-day indifference towards long-term perspectives will be remedied (Petts, 1980, 1984). Furthermore, observations of the effects of river impoundment made at a single instance, and particularly a short time after dam closure, will probably be unable to reflect the long-term consequences. Such failures to predict precisely the environmental costs of human activity cannot provide any justification for ignoring the probable or possible consequences (Petts, 1980, 1984). A wide and detailed data-base on regulated stream ecology would provide a firm foundation for authoritative environmental impact assessments and contribute greatly to a better understanding of the fundamental problems which arise from stream regulation (Armitage, 1984).

Fresh water on the planet, although a cyclical, renewable resource, has a limited available volume at any one time. In South Africa, an arid country, conventional freshwater resources, i.e. rivers, are being rapidly depleted. South Africa is fast reaching a point where there will be no more rivers available to be impounded and existing impoundments and water transfer schemes will no longer be able to supply the demand. This will necessitate the use of unconventional water resources such as recycling, desalination, icebergs etc. However, until the technology for harnessing unconventional water resources is developed for application in South Africa, we could manage our existing regulated rivers better if we understood how they work.

The present study provides information that can be used to assess the effect of future impoundments on cool, acid, blackwater, Cape mountain streams, and particularly the Palmiet river (see Introduction p 16). Together with the Buffalo river project (see comparison of data in O'Keeffe *et al.*, 1990) these unique data sets can also assist studies on

the possible effects of future impoundments on other river systems in the country. However, it remains to be seen whether the results of such studies will have any influence on the decision-makers or whether the pressure from human needs will result in "sacrificing" some, maybe all, of SA's rivers. The country may ultimately become an interlinking network of artificial water courses transferring water to wherever it is needed most. This may eventually decrease the amount of water available in an already severely water stressed country, since over-regulation and development of rivers within the catchments could severely affect the catchment's ability to harness available runoff.

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APPENDIX 1:

THE EFFECT OF IMPOUNDMENT ON THE PHYSICOCHEMISTRY OF TWO CONTRASTING SOUTHERN AFRICAN RIVER SYSTEMS.

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THE EFFECTS OF IMPOUNDMENT ON THE PHYSICOCHEMISTRY OF TWO CONTRASTING SOUTHERN AFRICAN RIVER SYSTEMS

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ABSTRACT

The downstream effects of six impoundments on their respective physicochemical conditions over two years are compared for two contrasting rivers. The impoundments studied included two on a cool, clear, clean, acid, and short system with a steep gradient (Palmiet River), and four on a warm, turbid, polluted, alkaline, and relatively long system (Buffalo River). Where possible, results are also compared against predictions of the Serial Discontinuity Concept (SDC) of Ward and Stanford (1983), and the 'recovery' (discontinuity) distances are estimated for a number of variables.

Major effects centred on changes in median spot temperatures and annual temperature ranges, particularly for dams regulating the upper reaches of both rivers. These upper river impoundments behaved similarly despite different release patterns, and caused only weak chemical effects, most of which recovered rapidly (within 3 km). Middle reach impoundments also behaved similarly despite different release characteristics, but they caused more pronounced changes and recovery distances were longer (up to 30 km).

Observed exceptions to the predictions of the SDC included alterations to nutrient regimes of receiving reaches downstream of *all* dams, annual temperature range was affected downstream of headwater dams on both rivers, and all impoundments on both systems depressed flow fluctuations. Although the specific predictions of the SDC model are not generally borne out, it is regarded as a useful tool for testing the effects of impoundment on rivers, and the concept of 'recovery distance' forms a useful practical framework for management of releases.

KEY WORDS Serial discontinuity Reservoir impact Water quality Pollution River recovery Release patterns Temperature Nutrient regimes Management

INTRODUCTION

South Africa is a relatively arid country (Alexander, 1985), and water is often the limiting factor for development. To develop the water resources, impoundments have been built on almost all large and medium-sized rivers, and most small ones. There are now 519 dams greater than 50 000 m^3 capacity, which together are capable of storing 50 per cent of the mean annual runoff from South African rivers (Department of Water Affairs, South Africa, 1986). Yet there is still a generally prevailing attitude that water flowing into the sea is 'wasted'.

Ward and Stanford (1983) have provided a detailed theoretical framework, the Serial Discontinuity Concept (SDC), to describe expected disruptions and subsequent recovery in rivers downstream of impoundments. Their ideas were based on the premise that an impoundment causes a discontinuity in the River Continuum (*sensu* Vannote *et al.*, 1980), and that natural riverine processes recover downstream to a new dynamic equilibrium. They referred to the 'discontinuity distance' as '... the longitudinal shift of a given parameter by stream regulation ...'. For the purposes of the research reported here, we interpret 'discontinuity distance' as *that length of stream which is required for any parameter to recover from disruption by impoundment*, and accordingly we shall refer to *recovery distance* as a better description of the processes that occur in receiving reaches downstream of impoundments.

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Ideally, in order to *measure* recovery distances, preimpoundment conditions should be known so that natural changes along the stream can be taken into account. If such data are available then the recovery distance is the length of stream required for a particular parameter to recover to levels which prevailed in the unregulated system. In many cases there are no such preimpoundment data, and our definition has to be modified such that recovery distance becomes *that length of stream which is required for any parameter to return to values close to those measured at the inflow to an impoundment, or to achieve a new dynamic equilibrium* (see also Byren and Davies, 1989; Palmer and O'Keeffe, in press).

Although there is a rapidly expanding literature describing the effects of river regulation (e.g. synthesis volumes by Ward and Stanford, 1979; Lillehammer and Saltviet, 1984; Petts, 1984; Craig and Kemper, 1987), few recovery distances have been quantified. Fraley (1979) found that temperatures equilibrated within 22 km of the Ennis Reservoir on the Madison River, a tributary of the Missouri, Wyoming. A decrease in dissolved oxygen downstream of a deep release dam at Lake Hume, on the Murray River, Australia, took 100 km to recover (Walker *et al.*, 1978). In response to changed physicochemical conditions, benthic invertebrate and fish species composition and population densities may all change drastically downstream of dams (e.g. Ward, 1976a, b; Krenkel *et al.*, 1979; Ward and Stanford, 1979; King and Tyler, 1982; Armitage, 1984), and Pearson *et al.* (1968) found that the macroinvertebrate community of the Green River took up to 150 km to recover downstream of Flaming Gorge Dam, Utah. In one of the few observations for South African rivers, Chutter (1969) measured a recovery distance of 8 km for the benthic macroinvertebrate community in the Vaal River below the Vaal Barrage, but found that unusually high densities of Simuliidae persisted for 50 km downstream of the Vaal-Haarts Diversion Weir (Chutter, 1973).

South African rivers have several marked differences from the north temperate rivers on which most regulated river research has been carried out. Many South African rivers tend to be turbid, steep and fast flowing, and in addition, the mean annual rainfall for the country is low (<500 mm a^{-1}) and unpredictable (Alexander, 1985). As a consequence, the effects of dams may be quite different from those in north temperate systems.

A joint research project on two contrasting rivers—the Buffalo River in the eastern Cape and the Palmiet River in the southwestern Cape—ultimately aims to describe the physicochemical and biotic effects of dams on these rivers. The effects of impoundment on the two rivers have individually been described in Byren and Davies (1989—Palmiet) and Palmer and O'Keeffe (in press —Buffalo), in which analyses are presented. This paper concentrates on a synthesis of information from the joint studies, comparing results from these very different rivers. Any effects of impoundment which are consistent between the two rivers should be widely applicable to the rivers of southern Africa and provide us with a way of predicting the likely effects of impoundment planned for other rivers in the region. In addition, we compare our results against the predictions of Ward and Stanford (1983).

STUDY SITES AND METHODS

Geographical details of the Buffalo and Palmiet rivers (Figure 1) together with detailed descriptions of methods are in Byren and Davies (1989) and Palmer and O'Keeffe (in press). The Palmiet River is a clear, clean, acid system with peak rainfall in winter (May–September), while the Buffalo is turbid and alkaline, receives considerable pollution in the middle reaches, and has peak rainfall in early and late summer (November and March). Table I lists the main attributes to each system, and Table II summarizes the main features of the impoundments studied on each river. We follow the convention of Byren and Davies (1989) and Palmer and O'Keeffe (in press), by referring to impoundments on the Palmiet as P1 and P2 and on the Buffalo as B1 through B4 (B1 and P1 are the upstream dams).

Monthly water samples were collected from 16 sites on the Buffalo River and 11 on the Palmiet between April 1986 and September 1987. These were analysed for conductivity, pH, alkalinity, soluble reactive phosphate (SRP), nitrate, nitrite, ammonium, dissolved oxygen, and temperature. Water flow data were supplied by the South African Department of Water Affairs for two continuous gauges on the Buffalo River and one on the Palmiet. Spot measurements of flows were taken at most sites on each sampling occasion. Methods were standardized for both rivers as far as possible but slight differences

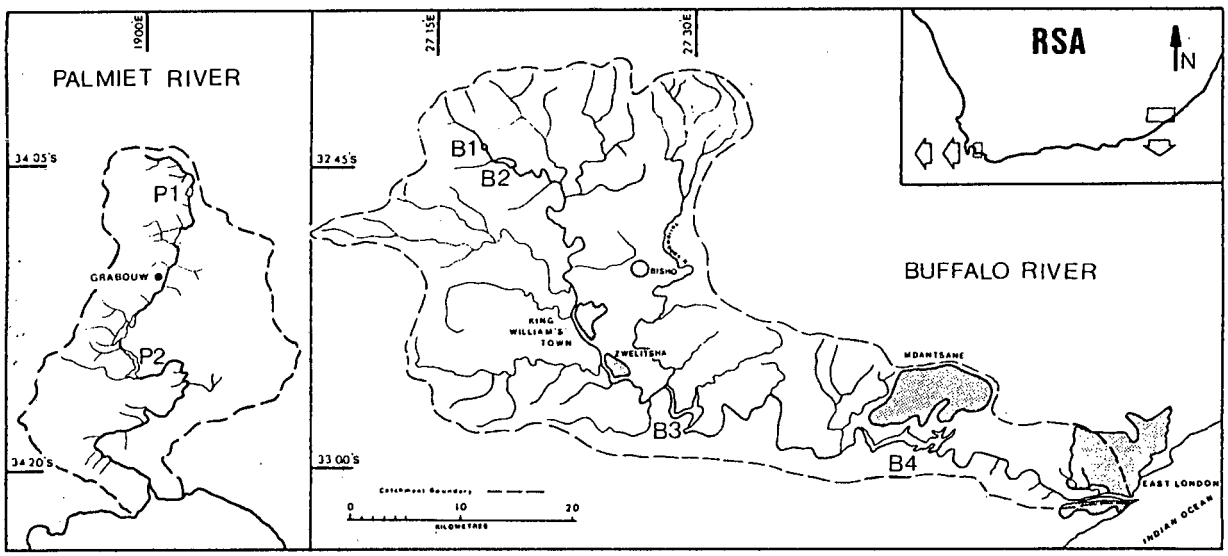

Fig. 1. Location of the two study areas and the impoundments (P1 and P2, and B1–4 on the Palmiet and Buffalo rivers respectively)

between the two programmes were mainly caused by logistical and supply considerations. For example, being a much larger system, the Buffalo required extended field trips, and on-site freezing materials were difficult to obtain and to maintain. Replicate tests on Buffalo River water samples frozen on site, compared to samples frozen later the same day, never showed more than 10 per cent differences.

Unless otherwise stated all data are presented as median values. The median provides a good reflection of base-flow trends and was selected in order to minimize the influences of drought and flood conditions, since it is very little affected by extreme values.

RESULTS

General comparison of physicochemical conditions down the two rivers

Figures 2 to 4 show the major trends in physical and chemical parameters in the two systems, as a function of distance from source. Flow rate in the Palmiet River is consistently higher than in the Buffalo (Figure 2a), increasing sharply in the lower reaches due to the inflow from two large tributaries downstream of P2. Abstraction for irrigation in the first few kilometres below P1 reduces flow in the middle reaches.

Table I. Physical attributes of the Palmiet and Buffalo river systems

Attribute	Buffalo	Palmiet
Catchment size (km^2)	1230	500
Length (km)	140	74
Stream order	4	4
MAR ($10^6 m^3$)	85	228
Source altitude (m)	1300	1133
Number of dams	4	5
Rainfall	summer	winter
Turbidity	turbid	clear
pH	alkaline	acid
Temperature	warm	cool
Pollution	severe (mid-reach)	mild (mid-reach)

Table II. Attributes of the six impoundments studied on the Palmiet and Buffalo river systems

Attribute	Buffalo				Palmiet	
	Maden B1	Rooikrans B2	Laing B3	BridleDrift B4	Neweberg P1	Arieskraal P2
Distance from source (km)	8	12	66	109	8	35
Capacity ($10^6 m^3$)	0·3	5·4	22·1	75·5	3·9	5·9
Catchment area (km^2)	31	48	913	1176	22	206
Altitude (m)	525	518	310	109	500	200
Height of wall (m)	10	13	25	47	18	26
Trophic status (Low/Enriched)	L	L	E	E	L	L
Release type (surface/bottom)	S	S	S	S/B	B	S/B
Compensation flow (Yes/No)	N	Y	N	Y	Y	Y

Lower runoff and continuous abstraction along the Buffalo River for irrigation and urban-industrial consumption keeps flow rates low, but water recycling between Kingwilliamstown and Laing Dam (B3) maintains higher flows in the middle reaches of the system. Abstraction for East London sharply reduces flow some 7 km downstream from Bridle Drift Dam (B4)

Figures 2b and 2c compare median spot water temperature and annual temperature ranges for the two systems. Median spot water temperatures in the Palmiet River were 2° to 8°C cooler than those in the Buffalo River (Figure 2b), varying from 12·5°C in the headwaters to 17°C in the middle reaches of the Palmiet, compared to 14°C in the headwaters to 23°C upstream of B3 in the Buffalo River. Total suspended solids (TSS; Figure 3a) were low (<5 mg l^{-1}) in the Palmiet River as a whole, and in the upper reaches of the Buffalo River. Increases in organic suspended solids in both rivers were largely the result of sewage effluents from Grabouw (Palmiet) and Kingwilliamstown/Zwelitsha (Buffalo). Despite the similar levels of suspended material in the upper reaches of the two rivers, the organic content of the suspensoids was consistently higher in the Palmiet River (37–96 per cent) compared to the Buffalo (12–49 per cent), but in both rivers, the percentage organic content showed a steady attenuation downstream.

The water quality of both systems deteriorated with distance downstream. Figures 3b–d show three major differences between the two rivers: respectively, lower conductivity, pH, and alkalinity in the Palmiet River. Interestingly, conductivities along the entire length of the Palmiet remained comparable to the near-pristine upper reaches of the Buffalo River (from 34 to 120 µS cm^{-1}). The major dissolved salts in both systems were chloride and sodium.

The Palmiet River is clearly acid, with the pH (Figure 3c) never exceeding 6·5 and alkalinities always less than 16 mg l^{-1} $CaCO_3$ (Figure 3d). The Buffalo, on the other hand, is neutral to alkaline throughout (pH 7–8·2), apart from the very top site, which had a median pH value of 6·1 and an alkalinity of 5 mgl^{-1} $CaCO_3$.

With the exception of the polluted sites on the Buffalo River, and nitrates in the headwaters, SRP nitrates, and nitrites in the two systems were similar (Figures 4a–c). SRP ranged from 15 to 50 µg l^{-1} in the Palmiet and in the upper reaches of the Buffalo, while typical levels in the middle and lower Buffalo ranged between 50–1000 µg l^{-1}. Ammonium levels (Figure 4d) in the Buffalo were surprisingly low (3–20 µg l^{-1} except for polluted sites), whilst in the Palmiet, typical values were between 40 and 95 µg l^{-1}. Both rivers were well oxygenated, although levels at the source of the Buffalo were depressed to 64 per cent saturation due to ground water inflow.

Effects of the Impoundments

By definition, impoundments reduce total flow downstream owing to evaporation and water abstraction. In the Buffalo River, water from impoundments B1, B2, and B3 is abstracted by pipeline to Kingwilliamstown/Zwelitsha. Water for East London and Mdantsane is abstracted from a weir 7 km downstream of B4. In the Palmiet, there is no direct abstraction from P1 but water for irrigation is

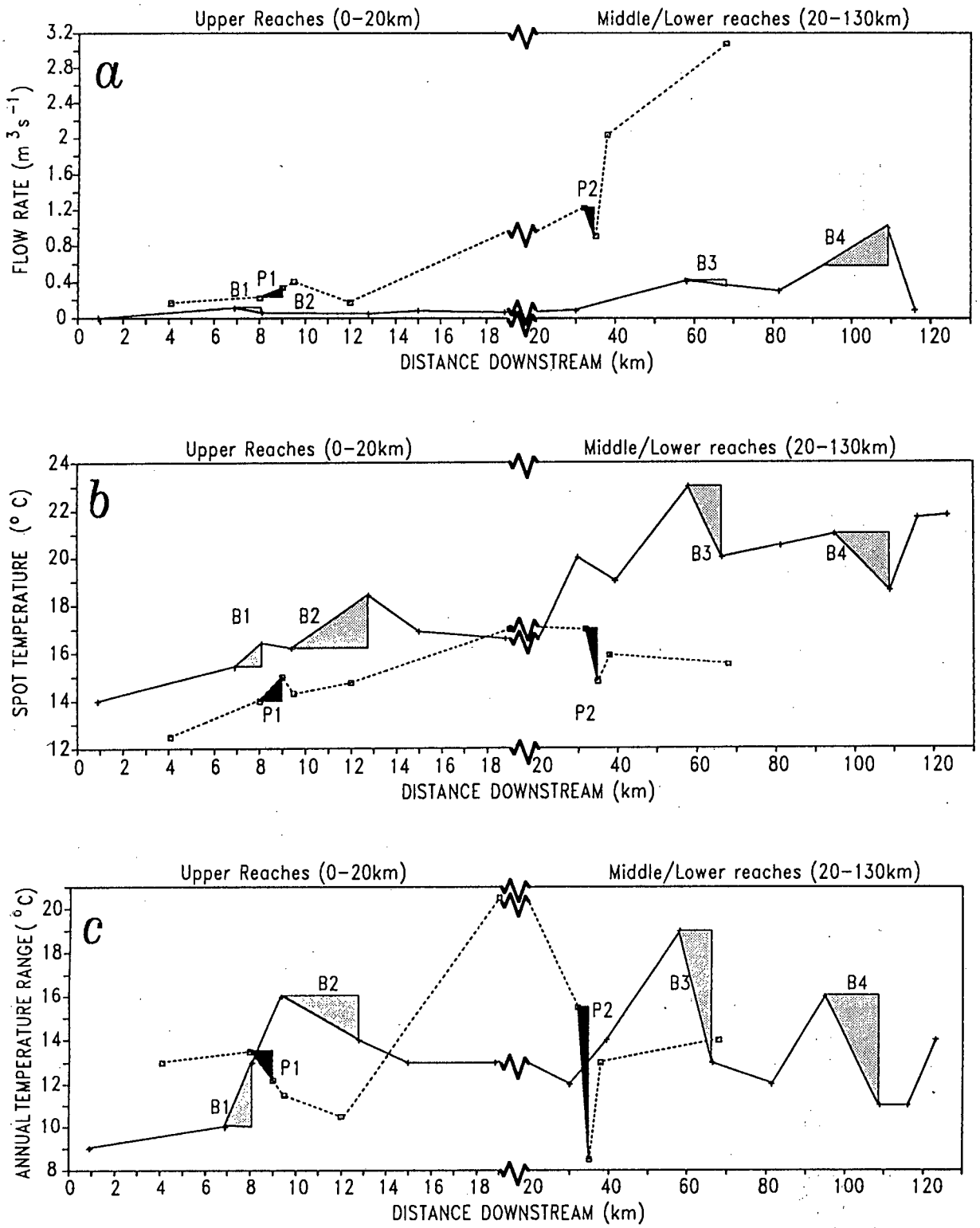

Fig. 2. (a) Median flows ($m^3 s^{-1}$), (b) median spot temperatures, and (c) annnual spot temperature ranges along the lengths of the Palmiet (dotted line) and Buffalo (continuous line) rivers. Shaded triangles indicate the positions of the impoundments and the dam walls are represented by the vertical axes of the triangles

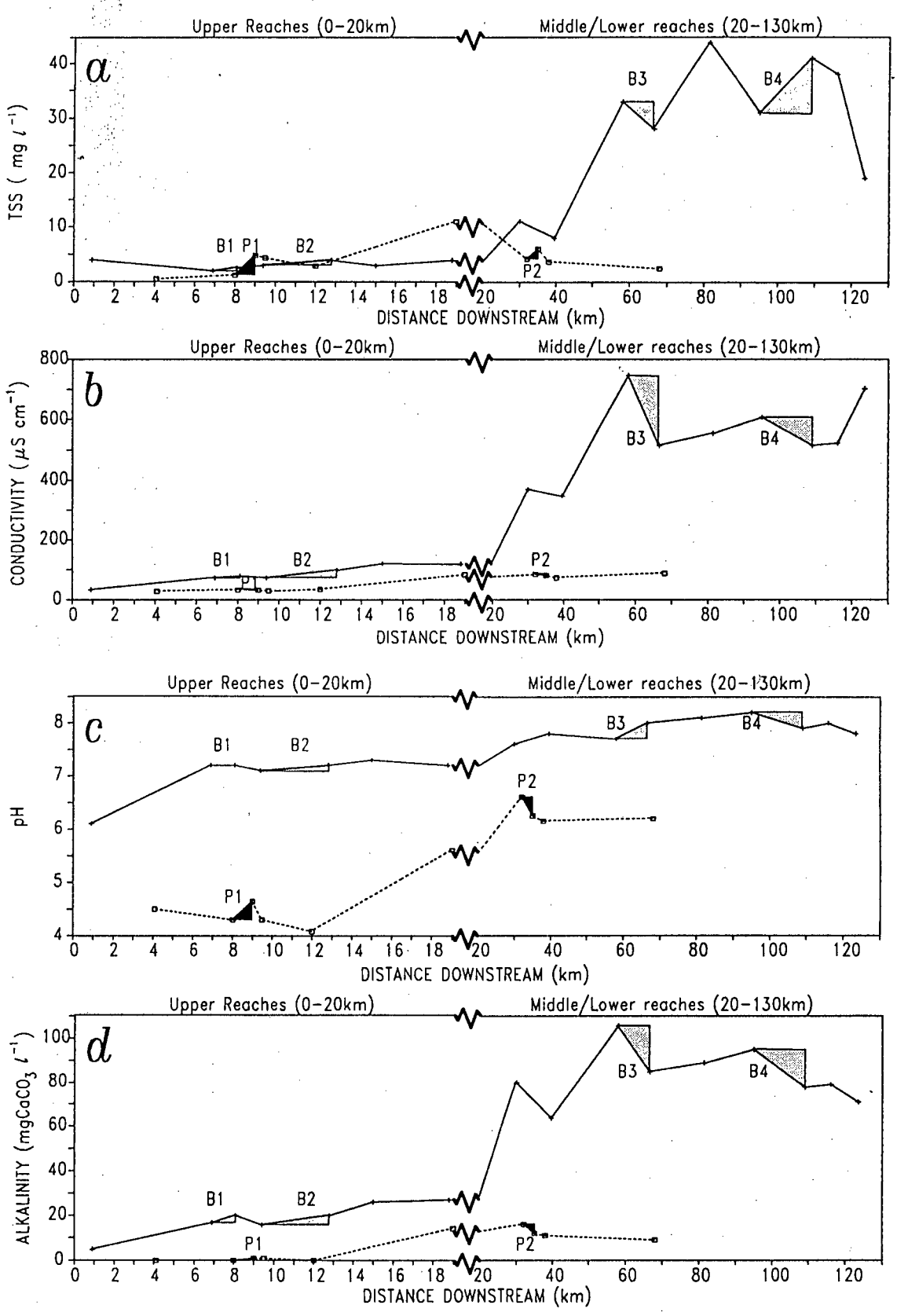

Fig. 3. Spatial changes in (a) suspended solids, (b) conductivity, (c) pH, and (d) alkalinity along the lengths of the Palmiet (dotted line) and Buffalo (continuous line) rivers. Shaded triangles indicate the positions of the impoundments and the dam walls are represented by the vertical axes of the triangles

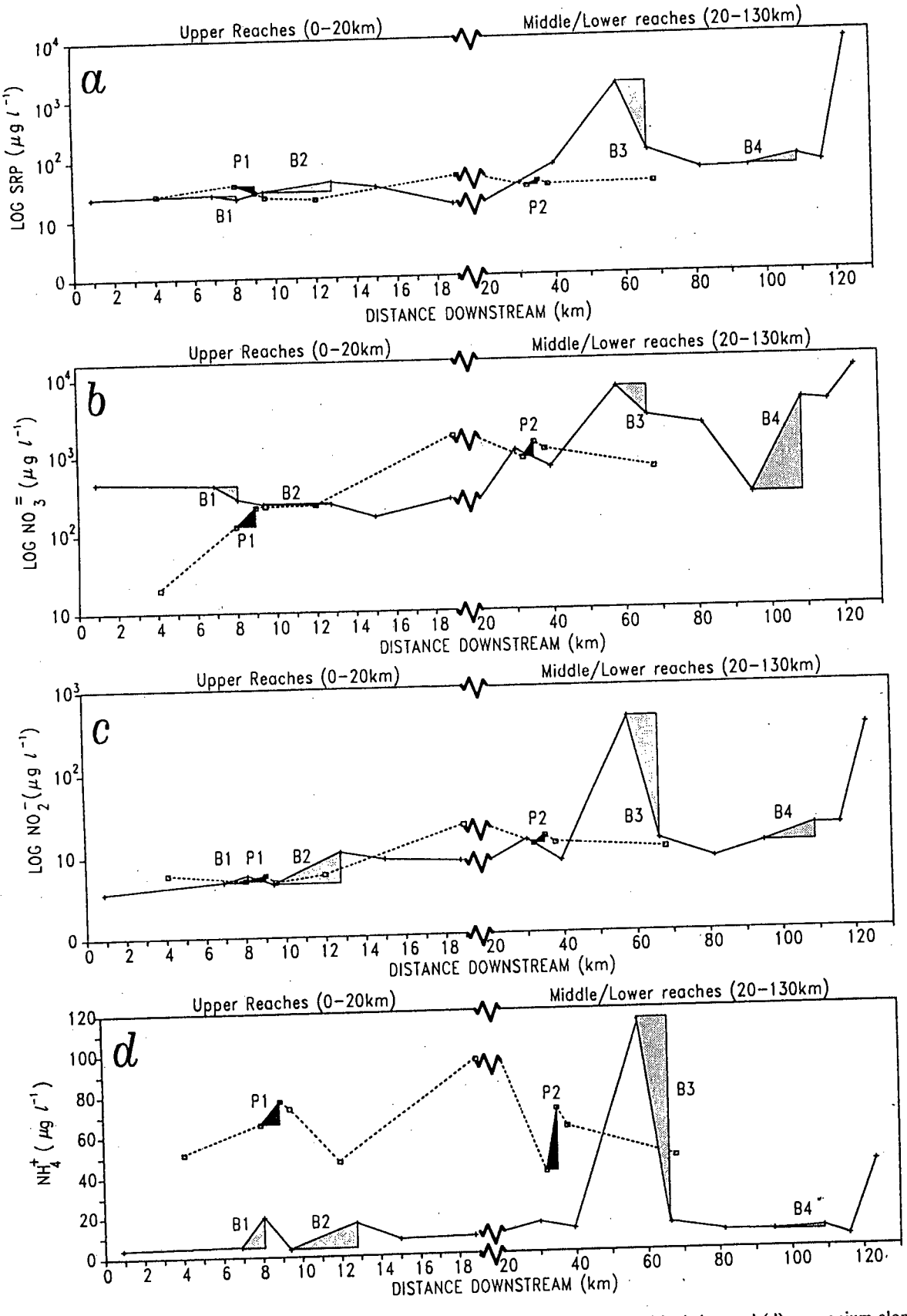

Fig. 4. Spatial changes in concentrations of (a) soluble reactive phosphate, (b) nitrate, (c) nitrite, and (d) ammonium along the lengths of the Buffalo (continuous line) and Palmiet (broken line) rivers. Note that (a), (b) and (c) have log-scale y-axes, while that for (d) is linear. Shaded triangles indicate the positions of the impoundments and the dam walls are represented by the vertical axes of the triangles

withdrawn from P2. Figure 2a shows the changes in flow rate down both systems based on spot measurements taken during sampling visits. Flow is reduced below all dams except P1 and B4, where an increase in flow is indicated. These increases are probably an artifact resulting from intermittent sampling.

One of the most important effects of the dams was the change in tailwater temperature regimes (Figures 2b, c). The median spot temperatures increased downstream of all three dams in the upper reaches (B1, B2, P1), and was reduced below those in the middle and lower reaches (B3, B4, P2). Median spot temperatures recovered within 2·2 km downstream of B2, within 3 km downstream of P2, and within 7 km below B4, and only partially recovered below P1 and B3. Annual spot temperature ranges (Figure 2c) were reduced downstream of all dams except B1 with no measurable complete recovery, although partial recovery was recorded downstream of B4 and P2.

TSS increased downstream of bottom-release dams (B4, P1, P2) (Figure 3a). Below P1, TSS increased from 1·2 to 4·8 mg l^{-1} and at P2 from 4·2 to 6 mg l^{-1}. These modifications recovered partially within 3 km downstream of P2. At B4, TSS increased from 31 mg l^{-1} upstream of the dam to 41 mg l^{-1} below the dam and recovered only slightly to 38 mg l^{-1} after 7 km.

Dams in the upper reaches of both rivers had no effect on conductivity (Figure 3b). In the case of alkalinity, however, increases occurred downstream of all upper impoundments (Figure 3d), recovering within 1·3 km below B1 and 3 km below P1.

SRP concentrations (Figure 4a) were highly variable, with generally higher concentrations downstream of B2, P2, and B4, recovering respectively within 2·2, 3 and partially within 7 km, whereas concentrations downstream of the other dams were generally lower. Nitrates increased downstream of bottom-release dams (P1, P2, B4) (Figure 4b), but concentrations below B1 decreased. B3 differed from the others in that influent water contained very high nitrate loads, particularly during low flows. Discharges from this dam were lower in nutrients compared to inflowing water, although concentrations were often higher than levels in the river upstream of pollution sources, particularly for nitrates (Figure 4b) (Palmer and O'Keeffe, in press). With the exception of B3, nitrites increased slightly below all six dams (Figure 4c), and recovery occurred within 1·3 km below B1 and within 3 km below P2. Ammonium (Figure 4d) increased downstream of B1, B2, P1, and P2, recovering below three of the four (within 1·3 km below B1, 3 km below P1, and 30 km below P2). Any effects of impoundment on dissolved oxygen in both systems were rapidly dissipated by turbulent release mechanisms.

Using all the variables, a dendrogram based on the Euclidian Distance Method (Dixon, 1985) arranged the sites for the two rivers into five major groups (Figure 5). The first separation fell between the two polluted sites on the Buffalo (site 8 downstream of Zwelitsha and site 13 downstream of the Mdantsane sewage outfall) and all others on the two rivers, including the mildly polluted site at Grabouw on the Palmiet (site 6). A second separation fell between the middle and lower reaches of the Buffalo versus the upper reaches of the Buffalo together with the whole of the Palmiet. This split was followed by the separation of the polluted Palmiet site from all remaining sites, while all upper Buffalo sites then split from the whole of the Palmiet River. Within these main divisions, the Palmiet then showed a three-way separation between site 1 (pristine, extremely acid headwaters), the upper reaches from site 2 upstream of P1 to site 5, 3 km downstream of P1, and the lower reaches from site 7 to site 11 (upstream of the estuary, including P2). The Buffalo also showed a separation of the uppermost site (site 0) from all other headwater sites (down to site 5, 6·4 km downstream of B2). In the middle and lower reaches, sites 6 and 7, which respectively lie 18 and 27 km below B2, and which receive agricultural return flows but not urban/industrial effluent, are separated from the remainder.

DISCUSSION

Comparison of the Buffalo and Palmiet and their impoundments

The dendrogram (Figure 5) and comparisons of individual variables (Figures 2–4), indicate that the entire Palmiet approximates both physically and chemically to the first 20 km of the upper and middle

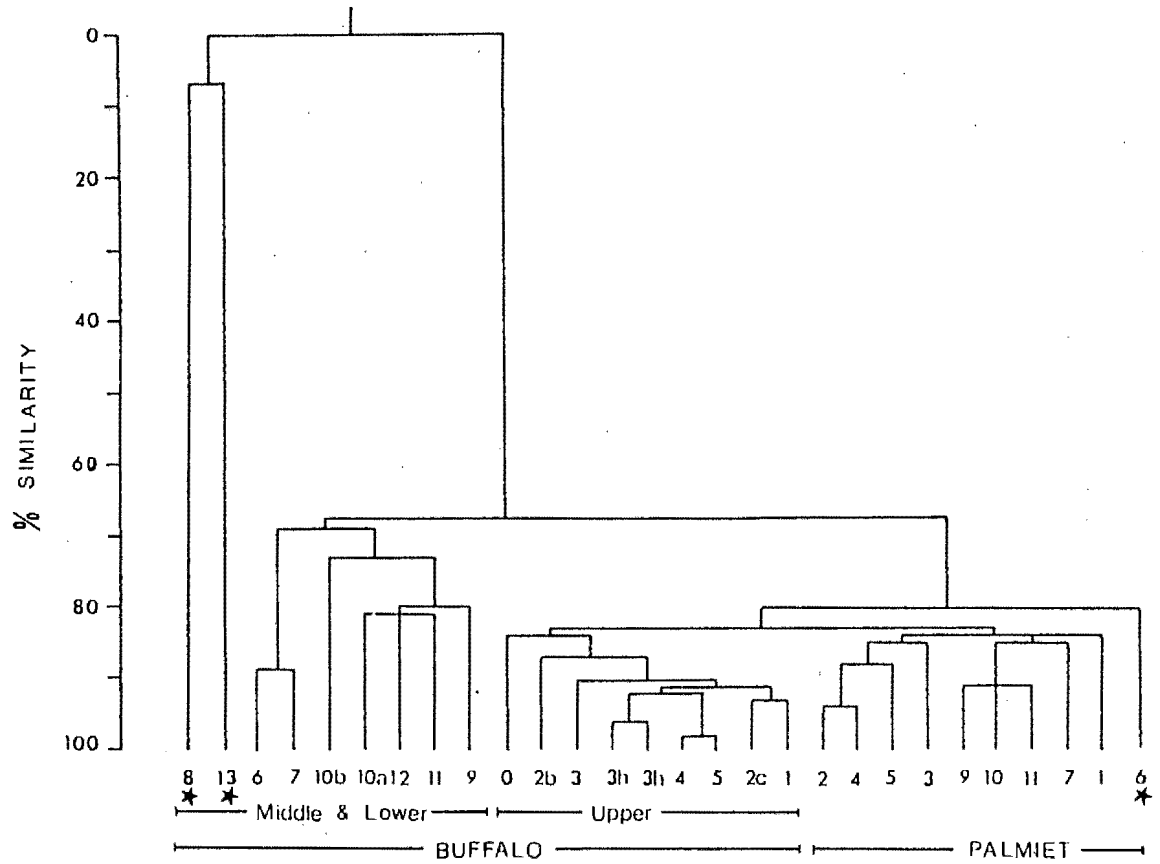

Fig. 5. Dendrogram of the physicochemical variables measured in the Buffalo and Palmiet rivers. Stars indicate polluted sites, which are significantly different (particularly in the Buffalo River) from the other sites. Numbers (0–13 for the Buffalo and 1–11 for the Palmiet) refer to sample site numbers (increasing downstream). Positions of the sample sites are respectively detailed in Palmer and O'Keeffe (in press) and Byren and Davies (1989)

sections of the Buffalo River, the differences being: greater flow volumes in the Palmiet, and different seasonal flow peaks; higher dissolved salt concentrations, alkalinity, and pH in the Buffalo, and a higher proportion of organic material in the suspended solids for the Palmiet, despite relatively similar TSS concentrations in the upper reaches of both rivers. From 20 km, downstream differences between the two systems increase, owing to greater mineralization rates and to increasing agricultural and urban/industrial pollution in the Buffalo River (Palmer and O'Keeffe, in press).

None of the variables measured were consistently affected by all six impoundments (Figure 6), emphasizing that generalizations about the regulatory effects of impoundments must be made with caution. Various aspects of the chemistry of receiving reaches altered by dams, have been discussed by Krenkel *et al.* (1979) (water quality), Rada and Wright (1979) (nitrogen and phosphorus), Petts (1984) (water quality and the effects of stratification), and Foulger and Petts (1984) (the effects of flow fluctuation on water quality). Hannan (1979) has reviewed the principal factors influencing the chemical composition of reservoir outflows, listing biological activity, age of impoundment, and wind effects, as well as many variables which are elements of these.

The effects of dams in the Buffalo and Palmiet Rivers in relation to the predictions of the SDC

The SDC (Ward and Stanford, 1983) predicts the effects of '... deep-release storage reservoirs, which thermally stratify and which do not release oxygen-deficient or gas-supersaturated waters' in different river zones, assuming that the streams are free from both pollution and other disturbances. Further, the SDC assumes the validity of the River Continuum Concept (RCC) of Vannote *et al.* (1980), one

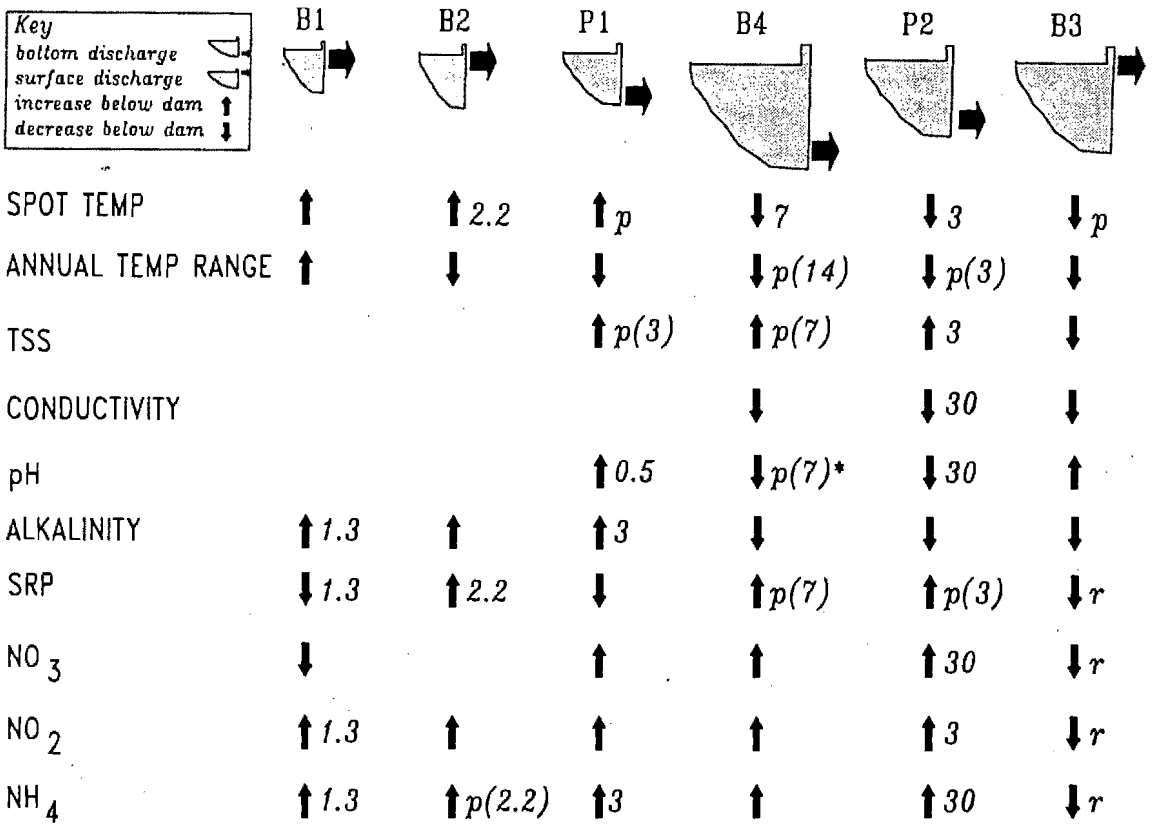

Fig. 6. Summary of the effects of the six impoundments (B1–4, Buffalo, and P1–2, Palmiet) on a variety of physicochemical features of the receiving reaches downstream of each impoundment. Arrow directions indicate whether or not the variable increases or decreases, numbers are measured recovery distances in km, 'p' denotes partial recovery and * denotes recovery during low-flow conditions. A blank space denotes no effect, while no number indicates that recovery distances could not be discerned. B3 receives polluted inflow and acts as a 'settling pond' in the river, so although recovery distances are not relevant, the river is 'reset' ('r') in terms of impoundment effects upon the major nutrients

characteristic of which is that headwaters are canopied and therefore allochthonous inputs predominate. The effects of size and nutrient status of impoundment are not discussed. None of the six impoundments investigated in this study comply with all these assumptions and we would not expect Ward and Stanford's (1983) predicted effects to be borne out in detail. Nevertheless we believe that the SDC provides a useful conceptual framework for the investigation of impoundment effects in general, and have therefore attempted to make certain comparisons of our results against the SDC.

Ward and Stanford (1983) predicted that damming headwaters will not affect the annual temperature range, presumably on the assumption that closed-canopy, spring-fed upper reaches will be buffered against seasonal temperature variations. In the Buffalo, where such conditions prevail, the temperature range downstream of B1 (surface release) increased by 3°C, while the range below B2 (also surface release), in a more open-canopied section of the catchment, decreased by 2°C. In the Palmiet, the range downstream of P1 (deep release in an open-canopy catchment) was depressed by 2°C. In the middle and lower reaches of both rivers, annual temperature range was reduced by all three impoundments (P2, B3, and B4). Other temperature predictions of the SDC include summer warming downstream of surface-release reservoirs. This was certainly the case downstream of B1 and B2 where median summer temperatures increased by 4 and 3°C, respectively.

In addition, the SDC predicts that no changes in nutrient availability will occur below dams on rivers smaller than sixth order (*vide*: Figure 3 in Ward and Standford, 1983). In our studies, however, available nutrients (SRP, NO_3, NO_2, NH_4) all increased below P2 and B4, but all decreased below B3 (because of

its reduction of the very high nutrient loads entering the impoundment). Nitrites and ammonium increased downstream of P1, B1, and B2, but nitrates and SRP showed variable changes downstream of these dams (Figure 6). Ward and Stanford's (1983) discussion of nutrients (their p. 36) is somewhat confusing because it equates availability with other plant requirements such as light and substratum type. It is not clear, therefore, why such predictions concerning no change in nutrient availability should have been made, especially as Soltero *et al.* (1973) are quoted as providing evidence for greater nitrate concentrations in outflowing reservoir waters.

For the reasons stated above, and also because in our study upper-reach impoundments do not meet all of the SDC criteria, those predictions of the SDC which we have tested so far are not generally borne out. Predictions of the effects of dams in the middle and lower reaches, however, have generally been correct for our systems. Further, Ward and Stanford's idea of discontinuity (recovery) distances, forms a useful practical framework for summarizing the disturbances caused by dams. We were not able to identify recovery distances in all cases, probably due to other confounding changes in the rivers such as tributary inflows and agricultural, urban, and industrial runoff. Where we have been able to assign recovery distances (Figure 6), these are averages which may change in response to flow rates and to season. It is also important to note that these averages may not reflect the recovery distances during critical conditions (such as very high or very low flows), which may be limiting events for much of the biota.

Bearing these factors in mind, some general effects of our impoundments can be described. We identified the following variables as those most likely to be important in governing the changes downstream of any dam: the position of the dam along the river; the size and depth of the impoundment; the release mechanism (surface or bottom) of the dam; and the pollution status of the inflowing water. An analysis of the similarities in the effects of the various dams investigated in this project, compared with the common factors between the dams (Table III), leads to the following conclusions:

1. There are no effects common to all six of the dams.
2. The position of the dam along the river appears to be the most important factor governing the type of effects caused downstream of a dam, while the marked differences between the two rivers appears to have very little influence on the type of effects.
3. The effects of size and depth of the impoundments are difficult to disentangle from position along the river since all the small dams are in the upper reaches and the larger dams are in the middle and lower reaches, but the larger impoundments (as might be expected) cause more intensive downstream changes, and these take longer to recover.
4. Release mechanism is of obvious importance in bottom-release dams which consistently reduce the temperature range, increase suspended solids, and increase all nitrogenous componds measured (Figure 6).
5. Influent pollution in B3 makes such a difference to downstream effects that B3 is not included in the analysis in Table III.

Using the above findings it is possible to identify three general groups of impoundments:

P1, B1, B2

Small, clean impoundments in upper reaches, causing major thermal modifications, and increasing or reducing the major nutrients. Despite some differences, probably caused by different release characteristics (Figure 6), these dams behave remarkably similarly in terms of their downstream effects (see Table III), and we conclude that their position in headwater reaches is probably the overriding factor governing their impacts. These impoundments appeared to cause only weak chemical effects, most of which recovered rapidly. However, changes in nitrate concentrations were large and we have, as yet, little knowledge of their impacts on downstream biotic processes. It should be noted that the upper reaches of the two rivers (first to third order streams) may be vulnerable to slight environmental changes. For example, small temperature changes have frequently been recorded to have profound effects on riverine biota (e.g. Ward, 1976a, 1985; Krenkel *et al.*, 1979; Ward and Stanford, 1979a; Marcotte, 1981; Armitage, 1984; Raddum, 1985).

Table III. Similarities and differences in the effects of different dams on the two rivers. Ten variables were measured for all dams, and qualitative similarities between pairs and groups of dams are listed below; e.g. for dams B1 and B2, 7 of the 10 variables showed similar changes above and below the dams. B3 is not included in the analysis, because it receives polluted inflow and downstream responses are quite different to the other dams (see text)

Grouping	Number similar (out of 10)	Common factors			
		River	Size	Zone	Release
B4:P2	10			lower	bottom
B1:B2	7	Buffalo	small	upper	surface
B1:P1	6		small	upper	
B2:P1	6		small	upper	
P1:P2	5	Palmiet			bottom
B2:P2	4				
B4:P1	5				
B1:B2:P1	5		small	lower	
B4:P1:P2	5				bottom
B2:B4	4	Buffalo			
B1:P2	2				
B1:B2:B4	2	Buffalo			
B1:B4	2	Buffalo			
B1:B2:B4:P1:P2	2				

P2, B4

Medium to large, deep-release impoundments of moderate quality in middle/lower reaches, reducing water temperatures, and increasing TSS and all major nutrients. Where they could be measured, disturbances recovered within 7 to 30 km. These dams caused more pronounced effects than the smaller, upper-reach structures as might be expected from their size and release characteristics. Despite differences in rainfall seasonality, the two dams had very similar impacts on downstream reaches (Figure 6; Table III).

B3

A medium-sized, surface-release impoundment which is heavily polluted. Except for alterations to temperature regimes, this impoundment had markedly different influences on the receiving reach, compared with all other dams (Table III; Figure 6). It is not possible to talk of recovery distances in relation to this structure, since the influent water was of very low quality, and the impoundment acted as a settling pond, improving downstream water quality (Palmer and O'Keeffe, in press).

CONCLUSIONS

The dendrogram (Figure 5) generally groups sites on the basis of levels of mineralization and organic enrichment down both rivers. It only partitions the rivers with respect to the position of impoundments at a much lower level of resolution. The implication is that, unsurprisingly, the effects of agricultural and urban/industrial pollution mask those of impoundment. However, the apparently 'low-intensity' effects of impoundment can have considerable consequences for the biota and for lotic ecosytem processes, and as such should not be ignored by water managers. For example, as we have pointed out earlier, even slight alterations to temperature regimes may have severe consequences for poikilotherms (e.g. Ward and Stanford, 1979a; Ward, 1985).

One of the main objectives of this joint project has been to provide water managers in South Africa with general guidelines on the ecological effects of impoundment, which can then be incorporated into water resource management plans. We have now provided estimates for the typical intensity and longitudinal duration of many of the physicochemical consequences of impoundment. Although the two rivers are different in many important aspects (such as geology, size, seasonality, volume of flow),

responses to impoundment are remarkably similar. We therefore have a strong basis for extrapolating the results of these projects to other river regulation schemes. The predicted effects of impoundent should be related to within-river variables such as water temperature, flow volume, suspended solids, and nutrients, and these should be the focus of future preimpoundment investigations. The type and intensity of these effects depend more on the size, position, pollution status, and release mechanism of the impoundment than they do on the type of river.

Recovery distances are a measure of how far downstream the impacts of impoundment may be expected to have a significant effect. For small dams in the upper reaches of both rivers, physicochemical conditions reequilibrated within 3 km, but larger dams in the middle and lower reaches caused changes which persisted for up to 30 km. These recovery distances may be strongly related to flow volumes. For example, in the Buffalo River, recovery distances for nitrates, SRP, and chlorophyll *a* were longer during high flow than during low flow (Palmer and O'Keeffe, in press). The Great Fish River, also in the eastern Cape, has an MAR of 252×10^6 m^3, three times greater than the Buffalo River, and Palmer and O'Keeffe (unpublished data) measured recovery distances for physicochemical variables of between 25 to 86 km.

In using these results, it is also necessary to bear in mind that they relate only to the individual physicochemical variables measured during these projects, and that the effects on the biology of the rivers, which will be presented in further papers, may be quite different, as a result of more subtle and synergistic environmental effects of the dams.

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APPENDIX 2:

Raw Data

a) **Physico-chemical data (refers to Paper 1)**

DISCHARGE (m3 s-1)

	SITE									
MONTH	1	2	3	4	5	7	8	9	10	11
2/86	0.5900	0.2236	2.5812	1.5081	1.2128	1.9089	1.6701	1.5002	1.4612	1.9672
3/86	0.3740	0.0823	0.2128	0.4107	0.4665	0.4352	1.8338	0.6212	0.6928	1.6833
4/86	0.3271	0.6298	0.2082	0.1705	0.1385	4.0862	3.5611	1.0107		
5/86	0.1672	0.1643	0.1744	0.1953	0.1298	1.4058	1.3358	1.1235	1.9521	
8/86	0.1644	1.1089	0.1722	0.8390	0.6970		3.2965			
9/86	0.1938	0.2589	0.1646	0.3686	0.1738	3.5371	1.8782	2.3660	4.6822	
10/86	0.0871	0.1606	0.1899	0.1370	0.1445	1.0449	0.6822	0.3257	1.6780	3.0783
11/86	0.0476	0.1473	0.3738	0.3201	0.1171	0.2730	0.8192	0.9085	0.7415	1.6119
12/86	0.0168	0.0282	0.4192	0.2039	0.1639	0.1663				0.8753
1/87	0.0159	0.0381	0.3266	0.3472	0.1041	0.1704	0.3171	0.6321	0.3545	
2/87	0.0340	0.0309	0.6138	0.5082	0.1983	1.0041	0.3723	0.4174	0.4648	1.0962
3/87	0.0045	0.0307	0.3417	0.4939	0.0861	0.3232	0.3277	0.8138	0.8802	0.5929
4/87	0.5001	1.1591	0.1748	0.2545	0.0978	1.2552	3.8714	0.4557		
5/87						0.1662	2.4544	0.9436		
6/87	0.2002	0.5218	0.7079	0.5481	0.4090	0.0533		0.5858	2.1113	
7/87	0.0768	0.4542	0.6807	0.5929	0.3239	2.4863				

WATER TEMPERATURE (oC)

	SITE										
MONTH	1	2	3	4	5	6	7	8	9	10	11
2/86	19.0	20.5	21.0	21.0	21.5	26.0	21.0	25.0	17.5	19.0	26.0
3/86	18.5	20.0	18.5	19.0	20.0	23.0	18.5	20.5	20.0	20.5	22.0
4/86	12.5	15.0	15.5	15.0	15.5	17.0	17.0	17.0	18.0	18.0	17.0
5/86	12.0	13.0	15.0	14.3	14.5	20.0	15.5	15.0	14.5	15.8	15.5
6/86	8.0	9.0	11.0	10.0	11.0	11.5	11.5	12.0	12.5	12.5	13.0
7/86	9.0	10.5	10.5	11.0	11.5	13.5	12.0	12.5	12.5	12.5	13.0
8/86	9.1	11.0	10.5	11.5	11.4	13.0	12.0	11.1	11.6	12.0	12.0
9/86	9.0	11.0	11.5	12.5	12.0	13.3	13.0	12.5	12.0	13.0	13.5
10/86	15.0	18.0	14.0	13.0	15.0	17.0	17.0	19.8	12.8	16.0	19.0
11/86	20.8	22.5	16.2	16.2	19.0	32.0	25.5	24.4	14.8	18.8	24.0
12/86	21.0	20.2	19.0	19.0	20.0	27.0	27.0	22.9	15.5	17.2	23.2
1/87	18.1	18.0	19.5	19.4	19.0	20.3	22.2	21.5	16.1	17.0	22.8
2/87	20.0	21.2	20.0	20.5	21.7	30.2	22.5	29.0	17.2	18.0	23.1
3/87	20.0	21.5	20.0	21.5	22.0	27.5	25.0	23.0	18.0	24.5	23.0
4/87	11.0	11.5	14.0	14.0	14.0	14.5	15.0	13.5	18.0		14.5
5/87	13.0	14.0	14.0	14.5		14.0	17.0	14.5	15.0	15.0	15.5
6/87	9.0	9.5	11.0	11.0	11.5	12.0	13.0		13.0	12.0	12.0
7/87	8.0	9.5	10.4	10.7	11.0	12.0	12.0	11.5	12.0	11.5	12.0
8/87	8.0	9.4	9.3	10.2	11.0	11.5	11.5	12.0	11.5	12.0	12.0
9/87	11.0	12.1	15.0	14.2	14.0	14.5	14.8	13.0	13.0	13.2	12.2
10/87	15.5	19.0	20.0	21.0	18.3	21.5	20.5	21.1	14.8	19.0	20.0

ALKALINITY (mg l-1 HCO3-)

	SITE										
MONTH	1	2	3	4	5	6	7	8	9	10	11
2/86	0.0151	0.0352	0.0201	0.0302	0.0251	0.1357	1.1306	0.0352	0.2111	0.2112	0.1026
3/86	0.0000	0.0267	0.0133	0.0133	0.0133	0.2132	1.7498	0.0000	0.2753	0.2398	0.0662
4/86	0.0000	0.0000	0.0000	0.0000	0.0000	0.0133	0.1821	0.0000	0.2842	0.1999	0.0662
5/86	0.0000	0.0000	0.0000	0.0000	0.0000	0.0711	0.0133	0.0000	0.0933	0.1066	0.0799
6/86	0.0153	0.0000	0.0000	0.0000	0.0000	0.1737	0.0711	0.0000	0.1079	0.0781	0.0491
7/86	0.0000	0.0105	0.0105	0.0000	0.0000	0.1026	0.0632	0.0000	0.0623	0.0351	0.0360
8/86	0.0000	0.0000	0.0000	0.0000	0.0000	0.1174	0.0862	0.0000	0.0671	0.0645	0.0934
9/86	0.0000	0.0000	0.0000	0.0000	0.0000	0.0537	0.0086	0.0000	0.0749	0.0633	0.0797
10/86	0.0000	0.0000	0.0000	0.0346	0.0000	0.1548	0.1804	0.0000	0.0851	0.1123	0.1311
11/86	0.0000	0.0000	0.0096	0.0096	0.0096	0.3742	0.3205	0.0096	0.0973	0.0838	0.0934
12/86	0.0000	0.0192	0.0077	0.0096	0.0077	0.2194	0.4747	0.0192	0.1459	0.1267	0.1478
1/87	0.0000	0.0096	0.0294	0.0096	0.0096	0.2930	0.5540	0.0096	0.1689	0.1420	0.1017
2/87	0.0000	0.0550	0.0413	0.0366	0.0275	0.2108	0.3529	0.0275	0.2567	0.2200	0.0871
3/87	0.0000	0.0413	0.0275	0.0275	0.0275	0.2475	0.0438	0.0413	0.2750	0.2658	0.0688
4/87	0.0000	0.0000	0.0413		0.0275	0.2017	0.1604	0.0000	0.2475		0.0275
5/87	0.0000	0.0000	0.0138	0.0275	0.0138	0.0550	0.1558	0.0000	0.4079	0.1192	0.1375
6/87											
7/87	0.0000	0.0000	0.0000	0.0000	0.0000	0.1100	0.1100	0.0000	0.1192	0.1100	0.1100
8/87	0.0000	0.0000	0.0000	0.0000	0.0000	0.0688	0.0779	0.0000	0.0917	0.0688	0.0917
9/87	0.0000	0.0000	0.0000	0.0000	0.0000	0.0825	0.0917	0.0000	0.0825	0.0275	0.0458

pH

	SITE										
MONTH	1	2	3	4	5	6	7	8	9	10	11
2/86	3.90	4.20	3.70	3.90	3.90	4.90	6.30	4.70	5.20	4.50	5.70
3/86	4.40	4.00	4.90	4.30	4.45	5.60	7.30	4.40	5.90	7.10	5.60
4/86	3.10	3.00	3.65	3.80	3.55	4.00	6.00	4.10	6.70	6.00	5.50
5/86	3.90	3.85	4.20	3.75	3.50	5.00	5.30	3.40	4.40	5.30	5.50
6/86	3.10	3.50	3.90	3.85	4.10	5.40		3.70			
7/86	4.57	3.88	4.00	4.12	4.00	5.91	5.61	4.17	5.97	5.75	5.29
8/86	4.70	4.50	4.60	4.70	4.50	6.40	6.60	4.30	6.30	6.10	6.20
9/86	4.65	3.75	4.40	3.60	3.50	5.15	6.35	3.80	6.20	6.15	6.45
10/86	4.60	4.30	3.80	4.10	4.35	6.00	6.70	4.50	6.35	6.30	6.20
11/86	4.55	4.50	4.70	4.60	4.65	6.60	6.80	4.45	5.50	6.00	6.00
12/86	4.80	5.05	5.10	4.20	3.75	6.40	7.10	4.30	6.10	6.30	6.40
1/87	4.05	4.30	4.40	4.30	4.20	5.60	6.60	4.90	6.20	6.60	6.70
2/87	4.50	5.10	5.20	5.05	3.80	6.10	6.65	5.05	6.30	6.00	6.20
3/87	3.90	5.15	5.15	4.65	4.15	5.85	6.45	5.05	6.85	6.85	5.65
4/87	3.60	3.80	6.10	4.60	4.00	5.50	7.10	5.80	6.60		4.50
5/87	4.90	4.30	4.80	5.85	3.65	5.00	7.90	5.50	6.40	6.80	6.40
6/87	4.50	4.35	4.68	4.60	4.88	6.25	8.53		6.72	5.95	6.89
7/86	4.50	4.58	4.64	4.45	4.50	6.05	6.76	4.53	6.14	6.52	6.38
8/87	4.62	3.49	4.38	4.00	3.96	5.13	5.70	4.00	6.41	6.28	6.24
9/87	4.54	3.95	4.85	4.36	4.08	5.28	6.25	3.95	6.14	4.81	4.45
10/87	5.35	6.15	7.30	6.85	6.50	5.75	6.30	4.40	6.30	6.40	6.45

DISSOLVED OXYGEN (%saturation)

	SITE										
MONTH	1	2	3	4	5	6	7	8	9	10	11
2/86	91.40	94.44	98.88	98.84	96.33	81.31	83.15	92.23	97.41	98.92	95.18
3/86	91.77	91.77	97.67	105.38	108.05	94.25	60.86	74.75	95.55		95.46
4/86	100.00	100.00	98.73	100.31	95.14	94.04	92.41	101.49	101.48	98.84	103.59
5/86	102.02	104.15	101.51	97.21	100.00	89.55	95.44	99.29	98.24	100.00	97.46
6/86	97.76	99.82	100.00	93.92	97.11	72.85	100.00	97.31	98.24	100.28	99.07
7/86	101.10	99.45	101.51	101.14	103.97	95.01	107.51	102.87	102.87	105.68	103.16
8/86	102.17	96.36	100.00	101.70	93.30	81.19	64.00	100.00	100.00	100.00	100.00
9/86	97.12	97.56	104.75	96.11	97.16	101.57	91.58	90.53	101.19	102.59	102.98
10/86	96.11	93.47	100.31	95.05	94.79	90.62	87.37	95.51	96.12	86.46	91.89
11/86	97.12	97.56	104.75	97.16	97.16	101.57	91.58	90.52	101.90	102.59	102.98
12/86	107.45	105.51	121.58	105.63	107.89	96.99	109.94	89.82	106.38	106.77	97.74
1/87	91.95	95.51	106.74	93.18	96.59	44.83	100.00	83.24	95.70	98.97	91.76
2/87	95.92	101.55	105.51	96.13	96.50	101.90	92.17	88.89	95.67	91.79	92.37
3/87	92.13	94.38	95.45	89.66	90.80	75.95	90.59	79.21	93.16	96.24	92.70
4/87	99.02	100.00	92.78	94.85	95.92	56.38	95.96	98.00	94.62		92.16
5/87	97.94	100.00	101.03	97.92	100.00	84.85	97.89	95.00	97.98	98.99	98.00
6/87	100.00	98.13	104.76	97.14	100.95	96.12	99.03		100.00	99.05	103.70
7/87	99.54	97.01	100.00	99.04	99.05	89.90	98.10	95.28	96.19	98.67	101.87
8/87	99.08	102.75	100.92	97.17	105.24	87.74	99.07	96.19	98.15	98.15	101.85
9/87	100.00	97.92	95.79	93.81	96.91	90.82	93.37	99.03	98.08	99.03	100.00
10/87	92.79	93.00	96.13	92.68	96.88	80.87	95.21	96.90	99.29	92.51	90.41

CONDUCTIVITY (uS cm-1)

	SITE										
MONTH	1	2	3	4	5	6	7	8	9	10	11
2/86	25.3	35.8	26.6	27.9	29.3	69.0	175.6	53.3	60.6	63.5	76.8
3/86	31.5	33.9	28.2	30.4	34.0	95.8	256.0	70.6	73.3	70.0	81.5
4/86	47.6	53.6	42.4	47.7	55.6	68.6	101.5	97.4	106.5	97.5	132.3
5/86	35.1	31.5	36.3	37.1	42.4	96.0	91.0	64.7	84.5	91.1	74.4
6/86	28.1	40.1	43.4	58.1	76.1	115.7	48.4	63.0	87.9	90.0	96.5
7/86	20.0	32.6	40.4	41.1	44.3	72.3	64.1	31.4	81.1	72.6	76.9
8/86	19.9	29.6	29.3	29.2	33.1	77.0	90.3	40.1	79.2	73.1	106.6
9/86	22.4	34.5	27.3	30.0	35.7	81.4	73.6	46.0	75.1	72.7	80.1
10/86	17.9	26.9	26.5	23.5	27.9	113.7	69.4	36.7	54.4	76.8	93.8
11/86	19.1	27.3	19.9	21.8	24.4	118.4	76.9		60.9	51.4	70.5
12/86	17.8	29.4	24.1	17.2	17.0	74.6	88.2	49.4	72.3	64.8	112.5
1/87	28.2	42.1	29.4	27.4	29.0	83.6	111.0	47.8	79.2	71.6	88.1
2/87	27.9	31.9	24.9	26.5	27.2	72.4	95.5	44.5	88.5	76.0	69.0
3/87	29.3	33.9	26.1	30.3	28.4	60.7	91.2	74.0	90.1	74.5	62.6
4/87	54.7	54.5	45.5	45.6	59.1	106.1	51.0	69.4	108.9		103.8
5/87	29.3	38.0	32.9	38.3	41.3	55.4	77.1	56.1	67.7	68.2	132.4
6/87	33.2	44.9	32.7	35.4	39.6	140.1	78.9		90.5	81.0	140.3
7/87	37.0	44.6	44.0	42.2	40.2	140.5	114.7	46.5	119.0	108.0	116.7
8/87	24.7	33.5	35.1	38.5	42.3	92.2	64.2	40.2	92.2	90.6	116.8
9/87	20.5	25.2	43.8	27.5	44.9	66.0	84.6	29.7	80.4	47.2	42.4
10/87	25.5	27.0	38.4	28.1	28.8	83.9	67.7	38.4	79.0	66.1	86.7

TDS (mg l-1)

	SITE										
MONTH	1	2	3	4	5	6	7	8	9	10	11
2/86	23.25	31.00	30.00	37.25	36.72	88.75	121.75	52.00	77.00	77.00	73.25
3/86	34.25	38.25	44.75	47.00	49.50	100.25	190.75	31.50	81.75	74.75	83.50
4/86	69.25	74.75	63.00	57.00	63.00	84.25	88.50	76.25	92.00	85.50	120.75
5/86	58.50	62.25	61.50	71.50	66.50	153.50	84.00	58.00	76.50	78.00	81.50
6/86	23.25	35.00	37.50	50.50	67.50	99.50	80.00	52.00	86.75	90.75	101.75
7/86	25.50	36.25	41.00	37.25	44.00	68.00	73.00	33.75	92.75	89.00	85.25
8/86	39.75	50.00	49.50	49.75	53.50	107.75	86.00	33.00	75.25	82.25	97.00
9/86	41.00	43.25	38.75	42.00	47.25	85.75	89.00	43.75	81.25	81.00	96.25
10/86	44.75	51.25	46.75	41.75	44.75	144.75	86.50		71.00	71.75	98.00
11/86	27.75	33.75	30.25	28.75	35.75	121.00	95.00	54.25	83.25	76.75	95.25
12/86	38.25	52.25	43.75	41.75	50.50	93.00	88.00	48.00	83.25	83.50	93.00
1/87	33.25	44.75	38.50	38.75	40.00	82.75	81.75	49.00	82.50	102.75	84.75
2/87	30.00	35.25	32.31	24.75	34.25	89.00	94.25	60.25	84.25	78.25	72.00
3/87	25.00	34.25	36.25	38.00	38.50	81.50	82.50	57.50	89.00	80.00	78.50
4/87	47.50	55.25	49.25	47.75	60.50	105.75	71.75	74.00	75.39		87.00
5/87	30.50	38.00	36.25	41.00	49.00	59.00	87.25	80.00	68.50	73.75	107.25
6/87	43.28	43.50	42.75	47.25	47.25	160.50	89.00		87.00	75.00	129.50
7/87	34.25	41.00	40.50	38.75	40.00	148.75	101.00	48.50		87.50	116.50
8/87	35.25	41.75	44.75	40.25	47.75	92.00	88.25	44.25	97.75	86.25	98.75
9/87	38.00	33.00	54.75	35.00	38.00	78.00	91.25	38.50	88.00	58.00	53.43
10/87	32.00	37.25	51.75	39.50	43.75	99.75	84.50	47.75	79.25	79.75	83.50

Cl- (mg l-1)

	SITE										
MONTH	1	2	3	4	5	6	7	8	9	10	11
2/86	8.52	12.35	9.37	9.66	9.66	20.53	22.24	20.08	21.10	18.46	25.99
3/86	9.14	11.64	8.38	11.13	10.45	25.84	26.07	19.23	20.53	21.36	28.54
4/86	5.96	6.67	12.35	13.92	14.77	19.88	21.50	21.50	23.57	22.86	34.93
5/86	9.51	11.93	12.07	13.63	13.77	28.40	20.50	17.55	16.98	19.03	21.64
6/86	5.64	7.87	9.97	12.79	14.88	24.51	16.79	13.70	18.98	18.57	23.01
7/86	4.14	7.51	8.19	3.55	10.01	9.01	5.05	7.05	17.40	16.16	18.30
8/86	5.74	8.06	8.19	8.47	9.15	16.84	15.66	9.83	15.84	16.16	25.31
9/86	7.48	10.24	7.54	8.65	10.88	19.95	19.34	12.09	17.11	17.45	27.04
10/86	6.68	10.97	8.27	9.16	7.73	31.90	15.90	14.95	17.59	14.57	25.45
11/86	5.74	9.56	7.84	7.78	9.56	29.98	14.43	14.62	16.77	15.36	24.19
12/86	7.92	12.87	8.71	9.00	9.42	25.46	21.86	16.79	17.34	18.11	28.90
1/87	8.31	12.74	9.58	9.85	9.36	20.45	21.47	17.97	18.16	18.83	22.43
2/87	8.95	11.75	9.16	9.58	9.63	18.58	25.68	15.85	20.18	19.79	23.54
3/87	9.28	12.44	9.73	9.56	10.26	19.71	20.21	16.86	19.37	19.09	22.45
4/87	9.38	10.17	10.17		14.07	19.55	15.12	16.94	20.33		23.20
5/87	8.60	10.43	9.38	9.64	10.95	14.60	19.55	14.60	17.43	18.51	29.19
6/87											
7/87	7.82	10.95	10.43	11.73	10.95	35.45	21.89	15.64	21.89	20.72	17.98
8/87	5.16	7.04	7.56	8.34	9.12	16.42	18.25	8.60	18.25	17.98	23.72
9/87	5.47	4.95	10.17	8.86	7.82	15.38	10.95	6.78	17.20	10.95	8.86
10/87	7.01	11.68	11.35	10.01	12.18	25.36	20.52	13.35	20.02	19.69	25.69
11/87	7.84	9.18	9.68	9.51	12.01	38.88	19.52	15.02	20.36	18.35	24.19
12/87	7.76	10.12	12.47	10.12	12.82	12.48	12.54	14.17	16.86	16.86	23.61
1/88		11.13	11.80	12.82	8.43	28.67	20.91	20.24	20.92	20.24	21.92
2/88	9.11	14.50	11.03	10.79	11.80	27.66	21.25	20.91	20.24	20.24	21.92
3/88	9.44	14.17	14.17	11.80	11.13	20.24	19.56	17.54	20.24	20.91	31.36

SO4= (mg l-1)

	SITE										
MONTH	1	2	3	4	5	6	7	8	9	10	11
2/86											
3/86	1.04	0.85	0.63	0.56	0.74	1.50	1.25	1.34	1.17	1.11	1.37
4/86	0.55	0.62	0.43	0.60	0.66	1.54	1.68	1.44	1.78	1.60	2.27
5/86	0.75	0.57	0.58	0.53	0.39	2.43	2.03	0.88	1.50	1.37	1.17
6/86	0.76	0.97	0.66	0.69	1.24	1.81	1.04	0.99	1.41	1.36	1.47
7/86	0.58	0.71	0.44	0.65	0.61	1.30	1.01	0.49	1.52	1.05	1.42
8/86	0.79	0.99	0.86	0.91	1.02	1.66	1.84	1.21	1.52	1.32	1.63
9/86	0.89	0.93	0.96	0.92	0.99	1.36	1.46	1.12	1.54	1.57	1.70
10/86	0.73	0.73	0.77	0.71	0.90	1.68	1.64	0.71	0.87	1.27	1.80
11/86	2.01	1.34	1.91	2.12		11.02	4.03	2.69		3.38	4.71
12/86	2.05	0.30	2.18	2.24	1.18	3.52	3.95	0.56	3.44	3.11	2.16
1/87	0.56	0.83	1.37	0.44	1.00	2.24	1.79	0.73	2.18	2.32	2.92
2/87	0.75	0.72	1.25	1.52	1.37	3.81	3.57	3.36		0.44	0.92
3/87	0.06	-0.57	1.13	0.15	0.91	1.56	1.31	1.51	1.78	1.60	1.72
4/87	0.40	1.16	0.56	0.25	0.97	3.35	2.76	2.50	0.59		0.56
5/87	1.16	0.29	1.31	0.39	1.47	2.44	2.32	2.32	2.60	1.06	1.66
6/87											
7/87	2.50	2.93	1.99	3.14	2.32	12.97	8.44	4.50	9.41	8.13	8.16
8/87	3.35	3.93	3.41	2.11	1.47	8.68	7.17	3.02	8.04	6.35	8.53
9/87	3.35	4.02	9.74	1.69	3.68	5.28	6.86	3.23	5.32	4.68	4.02

NO2 (ug l-1)

	SITE										
MONTH	1	2	3	4	5	6	7	8	9	10	11
2/86	0.00	5.06	2.30	2.30	3.68	33.59	11.04	5.98	15.18	1.38	10.50
3/86	1.38	3.69	5.06	2.76	4.14	15.18	7.82	4.14	7.82	8.74	7.82
4/86	5.98	5.06	5.98	0.92	5.06	15.18	12.42	12.88	12.88	9.66	10.12
5/86	7.82	6.90	8.28	4.60	5.06	28.07	15.64	15.64	16.10	14.72	4.60
6/86	9.20	11.04	10.58	9.66	14.72	22.08	14.26	17.48	16.56	19.32	15.18
7/86	9.66	12.42	11.96	9.66	11.04	29.45	15.18	11.04	17.48	13.80	19.32
8/86	9.66	10.12	10.58	11.04	11.96	16.56	18.86	12.88	12.88	12.88	13.80
9/86	10.58	10.12	13.34	12.88	11.50	15.18	15.64	16.56	20.24	13.80	15.64
10/86	10.12	7.36	11.04	10.58	10.58	32.21	22.54	10.58	17.02	14.72	16.56
11/86	7.82	5.06	10.58	10.58	10.58	71.32	11.50	10.58	21.62	15.64	16.56
12/86	1.95	1.30	4.20	3.22	3.87	21.34	9.20	3.43	10.38	8.30	8.30
1/87	1.30	0.97	3.87	3.22		16.00	5.33	2.66	11.76	8.30	6.92
2/87	1.30	1.30	3.22	4.52	5.17	27.34	8.00	10.30	10.03	9.69	9.00
3/87	0.65	3.24	2.58	4.84	4.52	18.00	6.00	7.55	15.22	6.92	10.38
4/87	7.13	7.78	3.87	4.20	4.52	72.68	11.34	19.23	7.61		13.84
5/87	3.24	4.54	4.52	5.49	6.46	11.34	19.34	13.05	12.45	12.45	11.76
6/87	2.96	4.54	5.81	7.10	8.00	15.57	16.00	18.54	24.91	12.45	10.38

NO3 (ug l-1)

	SITE										
MONTH	1	2	3	4	5	6	7	8	9	10	11
2/86	0.00	547.55	235.64	225.72	244.32	2179.03	359.04	0.00	811.09	0.00	879.30
3/86	0.00	408.65	241.22	233.78	324.93	2356.38	175.49	0.00	217.04	215.79	71.93
4/86	31.01	311.29	243.70	248.66	268.50	525.84	847.68	6.20	1021.30	711.87	548.17
5/86	3.72	97.36	256.10	303.85	253.62	1259.42	1493.82	7.44	1310.89	1056.65	670.95
6/86	9.92	119.06	234.40	674.05	533.29		1142.84	104.18	1462.82	1214.16	1019.44
7/86	0.00	80.61	222.00	256.10	257.96	912.17		0.00			
8/86	104.80	163.71	143.24	137.66							
9/86	0.00	78.75	128.36	89.91	76.89	2239.18	1936.57	0.00		2094.70	2248.48
10/86	0.00	45.27	155.03	151.30	96.12						
11/86	4.34	45.27	200.91	240.60	126.50	1875.18	1185.01	0.00	2654.03	1609.16	1104.40
12/86	69.45	58.29	152.54	180.45	127.12	1940.29	223.24	28.52	2430.79	1078.35	466.94
1/87	58.29	166.81	87.43	88.05		691.41	527.71	16.12	1532.89	1321.43	287.11
2/87	34.11	203.39	35.35	33.49	58.91	1428.71	834.65	0.00	920.23	806.75	132.70
3/87	23.56	403.69	62.01	59.53	99.22	1224.08	539.49	0.00	249.28	58.91	170.53
4/87	19.84	73.79	219.52	179.21	231.30		718.08	0.00	931.39		159.99
5/87	62.63	125.88	336.71	282.77	281.53	1899.37	2004.78	8.68	1988.04	1144.70	1658.15
6/87	20.46	137.66	229.44	241.22	121.54		2613.72		2411.57	1160.21	1800.77

NH4 (ug l-1)

	SITE										
MONTH	1	2	3	4	5	6	7	8	9	10	11
2/86	46.39	277.25	102.16	100.72	47.65	256.13	35.74	176.35	230.86	102.16	159.20
3/86	54.33	157.94	220.21	125.99	49.10	108.66	35.74	33.03	129.96	185.74	179.06
4/86	38.45	145.84	91.51	116.78	50.36	75.63	114.08	46.39	256.13	95.49	51.62
5/86	55.59	49.10	70.21	59.57	72.92	228.15	47.65	46.39	54.33	94.22	34.48
6/86	116.78	98.19	76.89	53.07	76.89	61.01	189.71	37.02	55.59	38.45	34.48
7/86	84.84	64.98	26.53	29.06	22.56	64.98	34.48	33.03	47.65	35.74	49.10
8/86	75.63	57.04	57.04	55.59	67.69	102.16	70.22	92.77	63.54	62.27	70.22
9/86	55.96	53.79	19.31	73.10	21.48	51.62	23.65	19.31	173.46	25.81	32.31
10/86	74.91	22.20	215.16	294.04	25.63	130.50	42.78	19.49	57.76	22.20	98.19
11/86	17.87	27.08	27.62	39.71	27.62		36.82	63.36	40.61	20.06	20.22
12/86	96.39	36.10	46.93	73.28	31.41	35.38	19.31	37.18	158.66	61.73	78.34
1/87	21.33	65.52			26.90	93.86	24.37	19.31	79.06	41.70	44.95
2/87	17.69	74.55	77.25	73.10	54.51	251.08	16.97	13.90	73.46	63.90	32.49
3/87	19.13	266.42	79.06	88.27	66.61	75.45	37.18	65.16	180.50	183.75	79.06
4/87		64.26	175.63	176.17	192.05	267.68	120.94	119.85	155.95		27.62
5/87	51.26	67.69	105.95	83.39	45.85	88.08	89.53	225.26	63.72	205.59	48.01
6/87	25.27	74.73	39.71	38.74	45.13	119.31	62.81		67.87	50.54	38.27
7/87	16.06	47.29	22.56	17.15	23.47	95.67	79.96	40.61	50.72	42.60	39.89

PO4 (ug l-1)

	SITE										
MONTH	1	2	3	4	5	6	7	8	9	10	11
2/86	17.10	99.72	10.45	6.65	20.89	49.38	6.65	128.21	46.54	49.38	49.38
3/86	29.44	120.61	40.84	10.45	14.25	6.65	21.84	21.84	37.04	14.25	28.64
4/86	78.83	22.79	27.54	27.54	41.79	41.79	60.78	51.28	37.04	22.79	41.79
5/86	20.89	55.08	16.15	12.35	15.20	52.23	30.39	37.04	46.54	39.89	43.69
6/86	24.69	49.38	31.34	46.54	142.46	39.89	58.88	54.13	44.64	35.14	9.50
7/86	32.29	37.04	21.84	21.84	26.59	90.22	43.69	31.34	59.83	37.04	53.18
8/86		38.94	35.14	29.44	29.44	27.54	63.63	42.74	38.94	44.64	44.64
9/86	27.54	25.64	27.54	22.79	22.79	48.43	50.33	38.94	67.43	38.94	52.23
10/86	26.59	15.20	533.73	34.19	20.89	39.89	26.59	24.69	26.59	16.15	29.44
11/86											
12/86	36.61	16.02	45.77	23.68	17.20	25.76	15.02	21.10	24.91	21.80	33.16
1/87	18.30	16.02	22.89	15.06	15.06	25.76	8.59	12.06	21.80	15.57	12.06
2/87	11.44	11.44	16.02	15.06	19.37	68.68	23.61	24.12	24.91	18.68	18.09
3/87	11.44	45.77	16.02	23.68	19.37	51.51	12.88	27.13	31.14	31.14	21.10
4/87	36.61	50.80	43.48	25.83	25.83	121.26	40.78	63.32	24.91		36.18
5/87	20.60	22.89	32.04	15.06	19.37	55.80	51.51	36.18	24.91	31.14	21.10

b) Particulate matter data (refers to Paper II)

COARSE PARTICULATE MATTER, ORGANIC AND INORGANIC FRACTIONS AND % ORGANICS

DATE	SITE	CPM mg m-3	CPOM mg m-3	CPIM mg m-3	%ORG
3/86	1	0.26	0.26	0.00	100.0000
3/86	2	3.26	1.86	1.41	56.8548
3/86	3	1.60	1.07	0.53	66.9643
3/86	4	29.72	7.88	21.85	26.4957
3/86	7	114.00	101.58	12.42	89.1089
3/86	8	71.02	69.52	1.49	97.8954
4/86	1	50.00	39.00	11.00	78.0000
4/86	3	1753.00	33.00	1720.00	1.8825
4/86	4	3473.00	513.00	2960.00	14.7711
4/86	5	1029.00	61.00	968.00	5.9281
4/86	7	1169.00	32.00	1137.00	2.7374
4/86	8	530.00	164.00	366.00	30.9434
4/86	9	936.00	120.00	816.00	12.8205
4/86	10	549.00	105.00	444.00	19.1257
4/86	11	525.00	21.00	504.00	4.0000
5/86	1	7.71	7.32	0.38	95.0108
5/86	2	7.66	4.84	2.83	63.1111
5/86	3	1.91	1.69	0.22	88.3929
5/86	4	3.20	0.69	2.52	21.4660
5/86	8	2.39	0.59	1.80	24.5421
5/86	9	0.27	0.27	0.00	100.0000
5/86	10	0.54	0.45	0.10	82.5000
5/86	11	1.02	0.95	0.06	93.8272
6/86	1	9.47	8.88	0.60	93.7037
6/86	2	180.68	144.33	36.35	79.8831
6/86	3	2.05	1.35	0.71	65.5556
6/86	7	3.75	3.75	0.00	100.0000
6/86	8	9.62	6.76	2.85	70.3448
8/86	1	ERR	ERR	ERR	88.9952
8/86	2	14.59	10.07	4.52	68.9956
8/86	4	258.13	87.33	170.80	33.8319
8/86	5	1.25	1.00	0.25	80.0000
8/86	7	11.82	3.57	8.25	30.1915
8/86	8	0.53	0.45	0.09	83.8710
8/86	9	1.91	0.89	1.02	46.6667
8/86	10	1.17	0.98	0.19	83.7500
8/86	11	34.11	3.45	30.66	10.1080
9/86	1	14.62	1.01	13.61	6.8908
9/86	2	1.13	0.97	0.16	86.0759
9/86	3	2.14	1.23	0.92	57.2917
9/86	4	296.98	60.23	236.76	20.2800
9/86	5	2.86	2.00	0.87	69.7115
9/86	7	ERR	ERR	ERR	30.9091
9/86	8	8.05	5.62	2.43	69.8145
9/86	9	1.94	1.80	0.15	92.4324
10/86	1	1.08	0.55	0.53	51.1628
10/86	2	10.34	5.63	4.71	54.4715
10/86	3	12.41	9.20	3.22	74.0806
10/86	4	4.37	2.06	2.31	47.2296
10/86	5	3.82	2.99	0.83	78.2313
10/86	7	8.03	0.65	7.38	8.1365
10/86	8	1.79	1.00	0.79	55.6962
10/86	9	6.83	3.58	3.25	52.3810
10/86	11	1.75	1.39	0.36	79.3814
1/87	1	1.48	1.48	0.00	100.0000
1/87	2	4.86	1.41	3.45	29.0323
1/87	3	1.89	1.36	0.54	71.6418
1/87	4	9.49	1.57	7.92	16.5370
1/87	5	7.18	3.86	3.32	53.7313
1/87	7	10.14	2.20	7.94	21.7320
1/87	8	8.69	8.07	0.62	92.8571
1/87	9	4.38	3.77	0.61	86.1272
1/87	10	6.70	5.02	1.67	75.0000
1/87	11	2.20	1.79	0.41	81.4815
4/87	1	33.73	4.25	29.48	12.5926
4/87	2	26.39	21.75	4.64	82.4074
4/87	3	12.38	12.38	0.00	100.0000
4/87	4	120.49	23.97	96.52	19.8939
4/87	5	1.94	1.94	0.00	100.0000
4/87	7	25.12	23.21	1.91	92.4000
4/87	8	0.21	0.21	0.00	100.0000
4/87	9	34.94	22.26	12.68	63.7168
4/87	11	21.60	21.60	0.00	100.0000
6/87	2	8.71	5.34	3.37	61.2591
6/87	4	90.15	38.78	51.37	43.0129
6/87	5	8.69	8.22	0.47	94.5783
6/87	7	3.38	1.24	2.14	36.6667
6/87	9	0.79	0.79	0.00	100.0000
6/87	11	0.93	0.93	0.00	100.0000
8/87	1	4.85	3.00	1.85	61.9048
8/87	2	2597.57	102.82	2494.75	3.9582
8/87	4	5.06	3.14	1.92	62.0690
8/87	5	14.52	13.29	1.23	91.5054
8/87	8	1.61	1.05	0.56	65.1163
8/87	9	0.33	0.21	0.12	64.7059
8/87	10	15.97	13.79	2.18	86.3724
8/87	11	ERR	ERR	ERR	40.0000
10/87	1	3.32	0.76	2.56	22.9508
10/87	3	ERR	ERR	ERR	9.4279
10/87	4	66.60	2.68	63.92	4.0236
10/87	5	6.04	1.97	4.06	32.6797
10/87	7	2.49	0.35	2.14	14.0625
10/87	9	1.14	1.06	0.08	92.8571
10/87	10	6.80	4.67	2.12	68.7500
10/87	11	ERR	ERR	ERR	34.4262
12/87	1	2.72	1.88	0.84	69.1358
12/87	2	21.40	18.94	2.46	88.4937
12/87	3	6.91	4.65	2.26	67.2619
12/87	4	29.36	10.54	18.82	35.8944
12/87	5	4.54	1.60	2.94	35.2201
12/87	7	11.18	2.58	8.60	23.0769
12/87	8	49.95	48.07	1.88	96.2330
12/87	9	3.35	2.07	1.28	61.7021
12/87	10	6.38	2.46	3.92	38.5714
12/87	11	2.39	0.93	1.46	38.8060
2/88	1	ERR	ERR	ERR	100.0000
2/88	2	518.79	9.42	509.37	1.8151
2/88	5	12.38	10.99	1.40	88.7097

COARSE PARTICULATE MATTER, ORGANIC AND INORGANIC FRACTIONS AND % ORGANICS (contd)

DATE	SITE	CPM mg m-3	CPOM mg m-3	CPIM mg m-3	%ORG
11/86	1	1.14	0.94	0.20	82.2222
11/86	2	6.07	3.62	2.45	59.6552
11/86	3	15.15	8.72	6.43	57.5515
11/86	4	9.64	2.45	7.19	25.4144
11/86	5	13.55	7.96	5.60	58.7156
11/86	7	2.75	0.76	1.98	27.8107
11/86	8	11.20	10.60	0.60	94.6223
11/86	9	1.79	0.90	0.90	50.0000
11/86	11	2.40	1.23	1.17	51.2195
12/86	1	1.05	1.05	0.00	100.0000
12/86	2	15.99	14.12	1.86	88.3402
12/86	3	1.62	1.16	0.46	71.8750
12/86	4	21.81	6.48	15.32	29.7210
12/86	5	1.11	0.79	0.33	70.4545
12/86	7	96.27	48.71	47.56	50.5988
12/86	8	ERR	ERR	ERR	98.2143
12/86	9	ERR	ERR	ERR	29.6178
12/86	10	ERR	ERR	ERR	96.1995
12/86	11	5.53	5.45	0.07	98.6547
2/88	7	416.99	356.43	60.56	85.4766
2/88	8	43.72	43.72	0.00	100.0000
2/88	9	14.51	8.44	6.07	58.1602
2/88	10	82.55	77.62	4.92	94.0363
2/88	11	11.30	8.93	2.37	79.0323
4/88	1	6.32	4.78	1.54	75.6364
4/88	2	2.57	2.17	0.40	84.6154
4/88	3	4.37	2.77	1.60	63.3721
4/88	4	32.78	3.95	28.83	12.0601
4/88	5	4.84	0.73	4.11	15.0538
4/88	7	144.37	40.02	104.35	27.7209
4/88	8	18.57	17.07	1.50	91.9355
4/88	9	22.05	4.83	17.22	21.9064
4/88	10	4.47	3.14	1.33	70.2875
4/88	11	7.67	7.14	0.53	93.1159

FINE PARTICULATE MATTER, ORGANIC AND INORGANIC FRACTIONS AND % ORGANICS

DATE	SITE	FPM mg m-3	FPOM mg m-3	FPIM mg m-3	%ORG
3/86	1	0.48	0.48	0.00	100.0000
3/86	2	13.40	6.58	6.82	49.1159
3/86	3	4.70	0.77	3.92	16.4634
3/86	4	277.66	29.47	248.19	10.6130
3/86	7	126.70	8.47	118.23	6.6815
3/86	8	3.90	2.13	1.77	54.6512
3/86	10	6.81	3.09	3.73	45.2830
4/86	1	41.00	21.00	20.00	51.2195
4/86	3	4643.00	35.00	4608.00	0.7538
4/86	4	4743.00	215.00	4528.00	4.5330
4/86	5	2645.00	36.00	2609.00	1.3611
4/86	7	2612.00	29.00	2583.00	1.1103
4/86	8	1637.00	28.00	1609.00	1.7104
4/86	9	2536.00	168.00	2368.00	6.6246
4/86	10	657.00	41.00	616.00	6.2405
4/86	11	2348.00	24.00	2324.00	1.0221
5/86	1	8.83	7.36	1.47	83.3333
5/86	2	239.30	15.25	224.05	6.3745
5/86	3	1.86	1.14	0.72	61.4679
5/86	4	13.56	1.12	12.43	8.2921
5/86	7	14.23	3.76	10.48	26.3889
5/86	8	1.09	0.57	0.52	52.4194
5/86	9	11.26	5.12	6.14	45.4545
5/86	10	4.35	1.74	2.61	40.0000
5/86	11	2.51	1.45	1.05	58.0000
6/86	1	22.21	9.23	12.98	41.5482
6/86	2	4207.83	187.58	4020.25	4.4579
6/86	4	5522.05	142.91	5379.14	2.5880
6/86	7	42.86	9.07	33.79	21.1679
6/86	8	26.93	10.35	16.58	38.4236
8/86	1	ERR	ERR	ERR	39.5604
8/86	2	1558.51	14.04	1544.47	0.9006
8/86	3	17.00	3.09	13.91	18.1922
8/86	4	57.01	22.36	34.65	39.2259
8/86	5	2.22	1.58	0.64	70.9677
8/86	7	106.97	4.18	102.79	3.9063
8/86	8	1.03	0.55	0.48	53.3333
8/86	9	3.83	2.14	1.69	55.8333
8/86	10	14.33	3.05	11.27	21.3115
8/86	11	37.24	3.71	33.53	9.9647
9/86	1	1.92	1.13	0.79	58.9744
9/86	3	9.96	0.74	9.22	7.3991
9/86	4	169.85	12.35	157.50	7.2700
9/86	5	1.83	0.55	1.28	30.0752
9/86	7	ERR	ERR	ERR	51.6129
9/86	8	13.05	0.58	12.47	4.4699
9/86	9	2.31	1.39	0.92	60.0000
10/86	1	3.83	1.06	2.77	27.6316
10/86	2	243.17	3.11	240.06	1.2789
10/86	3	89.18	2.44	86.74	2.7306
10/86	4	5.14	2.09	3.04	40.7186
10/86	5	3.76	1.51	2.26	40.0000
10/86	7	54.71	2.19	52.51	4.0062
10/86	8	3.19	0.36	2.83	11.3475
10/86	9	6.35	2.64	3.71	41.6382
10/86	11	13.40	2.33	11.07	17.3835
1/87	1	2.28	1.37	0.91	60.0000
1/87	2	5.27	2.96	2.30	56.2476
1/87	3	3.05	2.37	0.68	77.7778
1/87	4	27.76	5.46	22.29	19.6809
1/87	5	14.14	4.71	9.42	33.3333
1/87	7	12.46	2.25	10.21	18.0851
1/87	8	5.64	4.35	1.29	77.1186
1/87	9	10.69	4.81	5.87	45.0237
1/87	10	8.06	3.91	4.15	48.4848
1/87	11	1.24	0.33	0.92	26.2295
4/87	1	17.49	7.25	10.24	41.4286
4/87	2	91.38	32.25	59.13	35.2941
4/87	3	2.62	2.62	0.00	100.0000
4/87	4	87.57	9.59	77.98	10.9489
4/87	5	13.23	4.84	8.39	36.5854
4/87	7	12.86	5.13	7.74	39.8438
4/87	8	0.27	0.27	0.00	100.0000
4/87	9	41.74	21.64	20.10	51.8519
4/87	11	24.92	8.31	16.61	33.3333
6/87	2	160.77	9.05	151.72	5.6270
6/87	4	919.05	14.81	904.25	1.6113
6/87	5	7.33	2.46	4.87	33.5714
6/87	7	28.32	1.58	26.74	5.5703
6/87	9	4.80	2.24	2.56	46.5753
6/87	11	4.42	2.73	1.70	61.6541
8/87	1	4.95	2.64	2.31	53.3074
8/87	2	31196.88	76.73	31120.15	0.2460
8/87	4	10.64	3.84	6.80	36.0656
8/87	5	20.97	13.55	7.42	64.6314
8/87	8	4.98	2.37	2.61	47.5655
8/87	9	2.61	0.66	1.95	25.3731
8/87	10	20.39	3.89	16.50	19.0834
8/87	11	ERR	ERR	ERR	49.2063
10/87	1	2.23	1.90	0.33	85.3659
10/87	2	520.37	263.20	257.18	50.5785
10/87	3	ERR	ERR	ERR	1.3088
10/87	4	13.86	2.03	11.83	14.6667
10/87	5	3.95	1.30	2.64	33.0000
10/87	7	59.97	50.47	9.49	84.1689
10/87	8	2.03	1.65	0.38	81.2500
10/87	9	7.87	2.88	4.99	36.5979
10/87	10	22.50	13.43	9.07	59.6789
12/87	1	40.49	25.74	14.75	63.5762
12/87	2	115.80	3.34	112.45	2.8866
12/87	3	15.14	4.39	10.75	28.9855
12/87	4	55.01	11.21	43.81	20.3710
12/87	5	10.39	3.71	6.68	35.7143
12/87	7	11.12	4.01	7.11	36.0825
12/87	8	4.52	1.30	3.22	28.7554
12/87	9	8.28	3.21	5.07	38.7931
12/87	10	5.05	2.31	2.74	45.7831
12/87	11	4.17	3.42	0.75	82.0513
2/88	1	ERR	ERR	ERR	100.0000
2/88	2	91.68	84.85	6.83	92.5508
2/88	4	311.38	141.33	170.05	45.3880
2/88	5	14.25	12.21	2.04	85.6698

FINE PARTICULATE MATTER, ORGANIC AND INORGANIC FRACTIONS AND % ORGANICS (contd)

DATE	SITE	FPM mg m-3	FPOM mg m-3	FPIM mg m-3	%ORG
11/86	1	1.44	1.01	0.43	70.1754
11/86	2	12.38	10.71	1.67	86.4865
11/86	3	31.90	13.04	18.86	40.8696
11/86	4	40.03	9.94	30.10	24.8227
11/86	5	12.91	3.18	9.72	24.6628
11/86	7	4.78	1.27	3.51	26.5306
11/86	8	31.66	15.60	16.06	49.2754
11/86	9	18.91	1.93	16.98	10.1813
11/86	11	1.41	1.11	0.29	79.1667
12/86	1	1.28	0.78	0.50	60.8696
12/86	2	12.94	5.42	7.52	41.8644
12/86	4	16.31	4.07	12.24	24.9641
12/86	5	3.09	1.85	1.24	59.8361
12/86	7	76.52	4.76	71.77	6.2147
12/86	8	ERR	ERR	ERR	28.0702
12/86	9	ERR	ERR	ERR	66.6667
12/86	10	ERR	ERR	ERR	40.8696
12/86	11	1.09	0.82	0.27	75.0000
2/88	7	20.86	12.10	8.75	58.0340
2/88	8	6.80	5.47	1.34	80.3571
2/88	10	70.92	63.21	7.71	89.1348
2/88	11	9.62	5.22	4.40	54.2654
4/88	1	8.28	5.15	3.13	62.2222
4/88	2	9.96	2.05	7.90	20.6349
4/88	3	11.37	2.44	8.94	21.4286
4/88	4	37.04	3.57	33.47	9.6346
4/88	5	3.85	1.15	2.71	29.7297
4/88	7	117.76	26.99	90.77	22.9196
4/88	8	17.97	5.99	11.98	33.3333
4/88	9	56.05	24.19	31.86	43.1579
4/88	10	13.49	4.00	9.49	29.6610
4/88	11	1.97	1.45	0.53	73.2394

VERY FINE PARTICULATE MATTER, ORGANIC AND INORGANIC FRACTIONS AND % ORGANICS.

	SITE	VFPM mg m-3	VFPOM mg m-3	VFPIM mg m-3	%ORG
3/86	1	1.60	1.30	0.30	81.08
3/86	2	36.60	9.90	26.70	27.05
3/86	3	40.26	5.55	34.70	13.80
3/86	4	248.19	20.96	227.24	8.44
3/86	5	16.55	11.08	5.47	66.96
3/86	7	17.78	6.49	11.29	36.51
3/86	8	3.53	2.81	0.72	79.49
3/86	10	10.80	4.11	6.68	38.10
4/86	1	24.00	22.00	2.00	91.67
4/86	3	1306.00	32.00	1274.00	2.45
4/86	4	2568.00	148.00	2420.00	5.76
4/86	5	1430.00	58.00	1372.00	4.06
4/86	7	1268.00	54.00	1214.00	4.26
4/86	8	436.00	42.00	394.00	9.63
4/86	9	1504.00	144.00	1360.00	9.57
4/86	10	290.00	44.00	246.00	15.17
4/86	11	490.00	28.00	462.00	5.71
5/86	1	69.87	27.88	41.99	39.90
5/86	2	358.51	23.94	334.57	6.68
5/86	3	54.95	8.27	46.68	15.05
5/86	4	63.62	11.07	52.54	17.41
5/86	7	47.97	4.35	43.62	9.07
5/86	8	4.99	2.82	2.17	56.49
5/86	10	15.44	3.81	11.63	24.65
5/86	11	19.80	10.15	9.65	51.27
8/86	1	ERR	ERR	ERR	72.63
8/86	2	1106.32	8.87	1097.46	0.80
8/86	4	2179.92	18.41	2161.51	0.84
8/86	5	14.90	6.16	8.74	41.35
8/86	7	104.91	6.55	98.37	6.24
8/86	8	5.15	3.40	1.75	66.00
8/86	9	4.34	1.34	3.00	30.88
8/86	10	2.23	0.53	1.70	23.68
8/86	11	54.14	16.47	37.66	30.43
9/86	1	16.27	11.70	4.57	71.90
9/86	2	49.39	7.33	42.06	14.85
9/86	3	22.19	3.44	18.75	15.49
9/86	4	300.01	49.64	250.36	16.55
9/86	5	14.18	6.80	7.38	47.96
9/86	7	ERR	ERR	ERR	31.28
9/86	8	5.83	2.01	3.83	34.42
9/86	9	6.35	2.12	4.22	33.44
9/86	10	9.49	3.47	6.02	36.54
9/86	11	30.43	8.91	21.52	29.27
10/86	1	17.52	12.59	4.93	71.84
10/86	2	291.00	23.20	267.80	7.97
10/86	3	97.97	9.26	88.70	9.45
10/86	4	123.81	37.83	85.98	30.55
10/86	5	43.40	17.24	26.17	39.71
10/86	7	25.70	2.84	22.85	11.07
10/86	8	1.81	1.22	0.59	67.50
10/86	9	15.71	5.77	9.94	36.74
10/86	11	57.36	23.71	33.65	41.33

DATE	SITE	VFPM mg m-3	VFPOM mg m-3	VFPIM mg m-3	%ORG
1/87	1	19.16	15.06	4.11	78.57
1/87	2	48.03	7.65	40.38	15.93
1/87	3	43.27	3.95	39.32	9.14
1/87	4	248.30	45.99	202.30	18.52
1/87	5	421.31	207.55	213.76	49.26
1/87	7	22.41	5.70	16.71	25.44
1/87	8	7.45	7.07	0.38	94.87
1/87	9	28.51	10.53	17.98	36.94
1/87	10	29.62	12.81	16.82	43.23
1/87	11	4.60	2.08	2.52	45.13
4/87	1	14.99	10.99	4.00	73.33
4/87	2	291.25	61.33	229.92	21.06
4/87	3	6.28	4.01	2.27	63.89
4/87	4	234.90	26.53	208.38	11.29
4/87	5	43.57	21.62	21.94	49.63
4/87	8	0.51	0.51	0.00	100.00
4/87	9	256.32	74.52	181.80	29.07
4/87	11	45.27	24.92	20.35	55.05
6/87	2	250.73	11.72	239.00	4.68
6/87	5	8.59	5.76	2.83	67.07
6/87	7	6.77	1.97	4.80	29.13
6/87	9	20.32	5.72	14.60	28.16
6/87	11	27.26	15.32	11.93	56.22
8/87	1	8.84	4.30	4.53	48.69
8/87	4	38.62	7.85	30.77	20.32
8/87	5	72.87	23.51	49.36	32.26
8/87	8	11.76	6.27	5.49	53.33
8/87	9	3.61	1.09	2.52	30.19
8/87	10	26.01	3.33	22.68	12.79
8/87	11	ERR	ERR	ERR	43.69
10/87	1	46.23	32.20	14.03	69.65
10/87	2	2607.89	605.53	2002.37	23.22
10/87	3	ERR	ERR	ERR	1.49
10/87	4	57.61	22.78	34.84	39.53
10/87	5	22.65	13.81	8.84	60.98
10/87	7	54.95	52.77	2.18	96.03
10/87	8	3.38	2.58	0.80	76.25
10/87	9	65.26	20.05	45.21	30.72
10/87	10	7.56	4.29	3.27	56.74
10/87	11	ERR	ERR	ERR	34.34
12/87	1	18.64	13.01	5.63	69.78
12/87	2	85.24	13.01	72.22	15.27
12/87	3	63.20	4.22	58.97	6.68
12/87	4	218.17	30.80	187.36	14.12
12/87	5	50.02	22.15	27.86	44.29
12/87	7	50.00	15.83	34.17	31.65
12/87	8	3.34	1.47	1.86	44.19
12/87	9	69.63	20.83	48.80	29.92
12/87	10	28.20	11.31	16.90	40.09
12/87	11	13.40	8.12	5.27	60.64
2/88	1	ERR	ERR	ERR	62.96
2/88	2	52.57	25.04	27.53	47.64
2/88	3	51.22	3.86	47.36	7.54

VERY FINE PARTICULATE MATTER, ORGANIC AND INORGANIC FRACTIONS AND % ORGANICS (contd)

DATE	SITE	VFPM mg m-3	VFPOM mg m-3	VFPIM mg m-3	%ORG
11/86	1	26.46	14.19	12.27	53.64
11/86	2	145.26	24.60	120.66	16.94
11/86	3	1055.54	27.32	1028.21	2.59
11/86	4	267.50	60.95	206.55	22.79
11/86	5	128.52	68.74	59.78	53.48
11/86	7	13.16	2.93	10.24	22.22
11/86	8	35.79	13.94	21.85	38.94
11/86	9	38.34	13.19	25.16	34.39
11/86	10	8.76	3.40	5.36	38.80
11/86	11	18.15	9.25	8.90	50.97
12/86	1	1.89	1.89	0.00	100.00
12/86	2	34.91	14.56	20.35	41.71
12/86	3	35.41	4.29	31.12	12.11
12/86	4	178.84	48.24	130.60	26.98
12/86	5	58.95	30.29	28.67	51.37
12/86	7	51.27	8.39	42.87	16.37
12/86	8	ERR	ERR	ERR	80.77
2/88	4	6982.58	1703.25	5279.33	24.39
2/88	5	69.51	45.18	24.32	65.01
2/88	7	24.68	14.12	10.57	57.19
2/88	9	152.78	62.87	89.91	41.15
2/88	10	56.51	22.26	34.25	39.39
2/88	11	14.95	8.66	6.29	57.93
4/88	1	21.70	14.25	7.45	65.68
4/88	2	39.52	13.67	25.85	34.60
4/88	3	123.47	23.56	99.91	19.08
4/88	4	333.88	62.39	271.48	18.69
4/88	5	61.22	33.11	28.11	54.08
4/88	7	85.63	23.87	61.76	27.88
4/88	8	17.17	6.49	10.68	37.79
4/88	9	305.04	107.24	197.80	35.15
4/88	10	41.28	13.09	28.19	31.72
4/88	11	21.91	11.68	10.23	53.30

ULTRA-FINE PARTICULATE MATTER, ORGANIC AND INORGANIC FRACTIONS AND % ORGANICS

DATE	SITE	UFPM mg l-1	UFPOM mg l-1	UFPIM mg l-1	%ORG
2/86	1	0.50	0.50	0.00	100.00
2/86	2	0.10	0.10	0.00	100.00
2/86	3	8.53	5.73	2.80	67.17
2/86	4	6.67	3.78	2.89	56.67
2/86	5	4.40	4.00	0.40	90.91
2/86	6	18.00	13.20	4.80	73.33
2/86	7	4.70	1.80	2.90	38.30
2/86	8	1.13	1.13	0.00	100.00
2/86	9	11.20	7.40	3.80	66.07
2/86	10	6.00	4.00	2.00	66.67
2/86	11	1.15	1.15	0.00	100.00
3/86	1	0.35	0.35	0.00	100.00
3/86	2	1.60	1.60	0.00	100.00
3/86	3	9.00	7.00	2.00	77.78
3/86	4	7.20	6.20	1.00	86.11
3/86	5	5.00	5.00	0.00	100.00
3/86	6	14.40	11.60	2.80	80.56
3/86	7	12.00	9.20	2.80	76.67
3/86	8	2.00	1.70	0.30	85.00
3/86	9	6.80	6.80	0.00	100.00
3/86	10	9.40	6.00	3.40	63.83
3/86	11	1.30	0.70	0.60	53.85
4/86	1	0.43	0.43	0.00	100.00
4/86	2	1.25	1.25	0.00	100.00
4/86	3	8.20	4.80	3.40	58.54
4/86	4	6.80	4.40	2.40	64.71
4/86	5	4.40	3.60	0.80	81.82
4/86	6	7.80	7.00	0.80	89.74
4/86	7	7.60	4.80	2.80	63.16
4/86	8	0.45	0.45	0.00	100.00
4/86	9	12.40	5.20	7.20	41.94
4/86	10	4.20	2.60	1.60	61.90
4/86	11	2.60	1.30	1.30	50.00
11/86	1	0.80	0.67	0.13	83.75
11/86	2	0.95	0.75	0.20	78.95
11/86	3	5.87	3.07	2.80	52.30
11/86	4	5.07	2.27	2.80	44.77
11/86	5	2.40	1.40	1.00	58.33
11/86	6	17.20	7.60	9.60	44.19
11/86	7	3.20	0.90	2.30	28.13
11/86	8	1.17	0.70	0.47	59.83
11/86	9	4.53	2.27	2.26	50.11
11/86	10	2.80	1.60	1.20	57.14
11/86	11	1.94	1.03	0.91	53.09
12/86	1	0.67	0.50	0.17	74.63
12/86	2	1.55	1.05	0.50	67.74
12/86	3	4.67	4.50	0.17	96.36
12/86	4	5.28	3.68	1.60	69.70
12/86	5	3.29	2.94	0.35	89.36
12/86	6	32.00	20.00	12.00	62.50
12/86	7	2.40	1.36	1.04	56.67
12/86	8	0.60	0.60	0.00	100.00
12/86	9	4.27	3.20	1.07	74.94
12/86	10	4.29	3.57	0.72	83.22
12/86	11	1.93	1.86	0.07	96.37
1/87	1	0.33	0.33	0.00	100.00
1/87	2	1.71	1.71	0.00	100.00
1/87	3	6.59	5.46	1.13	82.85
1/87	4	5.33	4.89	0.44	91.74
1/87	5	5.00	4.67	0.33	93.40
1/87	6	16.67	ERR	16.67	ERR
1/87	7	2.50	1.38	1.12	55.20
1/87	8	2.55	1.66	0.89	65.10
1/87	9	8.00	5.60	2.40	70.00
1/87	10	6.31	4.77	1.54	75.59
1/87	11	2.22	1.16	1.06	52.25
8/87	1	0.25	0.25	0.00	100.00
8/87	2	1.31	1.20	0.11	91.60
8/87	3	4.08	0.92	3.16	22.55
8/87	4	3.10	1.90	1.20	61.29
8/87	5	3.27	1.40	1.87	42.81
8/87	6	11.70	3.00	8.70	25.64
8/87	7	3.33	1.25	2.08	37.54
8/87	8	0.47	0.38	0.09	80.85
8/87	9	4.58	1.25	3.33	27.29
8/87	10	8.08	1.83	6.25	22.65
8/87	11	8.67	ERR	8.67	ERR
9/87	1	2.25	1.70	0.55	75.56
9/87	2	1.00	0.85	0.15	85.00
9/87	3	3.58	1.92	1.66	53.63
9/87	4	1.08	1.08	0.00	100.00
9/87	5	2.00	1.42	0.58	71.00
9/87	6	7.73	3.10	4.63	40.10
9/87	7	1.83	1.25	0.58	68.31
9/87	8	1.33	1.17	0.16	87.97
9/87	9	1.60	0.72	0.88	45.00
9/87	10	2.08	1.33	0.75	63.94
9/87	11	6.67	3.07	3.60	46.03
10/87	1	1.06	0.56	0.50	52.83
10/87	2	0.60	0.54	0.06	90.00
10/87	3	5.73	3.73	2.00	65.10
10/87	4	1.82	1.21	0.61	66.48
10/87	5	1.11	0.90	0.21	81.08
10/87	6	56.00	14.40	41.60	25.71
10/87	7	2.87	1.57	1.30	54.70
10/87	8	0.72	0.48	0.24	66.67
10/87	9	2.00	1.22	0.78	61.00
10/87	10	1.83	1.30	0.53	71.04
10/87	11	ERR	ERR	0.00	ERR

ULTRA-FINE PARTICULATE MATTER, ORGANIC AND INORGANIC FRACTIONS AND % ORGANICS (contd)

DATE	SITE	UFPM mg l-1	UFPOM mg l-1	UFPIM mg l-1	%ORG
5/86	1	0.10	0.10	0.00	100.00
5/86	2	1.14	1.09	0.05	95.61
5/86	3	5.00	3.00	2.00	60.00
5/86	4	5.00	3.00	2.00	60.00
5/86	5	3.20	2.53	0.67	79.06
5/86	6	6.40	3.20	3.20	50.00
5/86	7	6.00	4.00	2.00	66.67
5/86	8	1.00	1.00	0.00	100.00
5/86	9	7.80	2.00	5.80	25.64
5/86	10	4.40	1.10	3.30	25.00
5/86	11	1.13	0.67	0.46	59.29
6/86	1	1.80	1.30	0.50	72.22
6/86	2	5.20	2.10	3.10	40.38
6/86	3	11.60	2.80	8.80	24.14
6/86	4	13.00	2.80	10.20	21.54
6/86	5	16.40	6.00	10.40	36.59
6/86	6	42.80	8.00	34.80	18.69
6/86	7	15.71	1.57	14.14	9.99
6/86	8	1.60	0.63	0.97	39.38
6/86	9	37.33	2.13	35.20	5.71
6/86	10	8.20	0.00	8.20	0.00
6/86	11	7.47	1.87	5.60	25.03
7/86	1	1.40	1.40	0.00	100.00
7/86	2	3.71	1.12	2.59	30.19
7/86	3	4.70	1.26	3.44	26.81
7/86	4	6.00	3.18	2.82	53.00
7/86	5	3.76	2.16	1.60	57.45
7/86	6	102.40	20.80	81.60	20.31
7/86	7	42.20	7.20	35.00	17.06
7/86	8	5.80	2.13	3.67	36.72
7/86	9	36.00	8.80	27.20	24.44
7/86	10	31.20	6.40	24.80	20.51
7/86	11	21.60	6.40	15.20	29.63

DATE	SITE	UFPM mg l-1	UFPOM mg l-1	UFPIM mg l-1	%ORG
2/87	1	0.36	0.00	0.36	0.00
2/87	2	1.07	0.90	0.17	84.11
2/87	3	6.67	2.40	4.27	35.98
2/87	4	3.56	2.67	0.89	75.00
2/87	5	3.20	1.40	1.80	43.75
2/87	6	7.20	6.80	0.40	94.44
2/87	7	3.50	1.00	2.50	28.57
2/87	8	0.29	ERR	0.29	ERR
2/87	9	6.00	2.57	3.43	42.83
2/87	10	5.40	2.00	3.40	37.04
2/87	11	1.10	0.60	0.50	54.55
3/87	1	0.03	0.03	0.00	100.00
3/87	2	1.30	1.00	0.30	76.92
3/87	3	3.60	2.40	1.20	66.67
3/87	4	3.80	2.80	1.00	73.68
3/87	5	2.00	2.00	0.00	100.00
3/87	6	8.00	7.43	0.57	92.88
3/87	7	1.07	0.67	0.40	62.62
3/87	8	1.36	0.64	0.72	47.06
3/87	9	4.40	2.40	2.00	54.55
3/87	10	2.33	1.67	0.66	71.67
3/87	11	1.37	0.86	0.51	62.77
4/87	1	1.00	0.88	0.12	88.00
4/87	2	2.87	1.87	1.00	65.16
4/87	3	61.33	20.00	41.33	32.61
4/87	4	56.67	16.00	40.67	28.23
4/87	5	5.29	2.71	2.58	51.23
4/87	6	23.20	9.60	13.60	41.38
4/87	7	ERR	ERR	0.00	ERR
4/87	8	0.58	0.58	0.00	100.00
4/87	9	6.00	2.67	3.33	44.50
4/87	10	ERR	ERR	0.00	ERR
4/87	11	0.90	0.90	0.00	100.00

DATE	SITE	UFPM mg l-1	UFPOM mg l-1	UFPIM mg l-1	%ORG
11/87	1	0.38	0.28	0.10	73.68
11/87	2	1.02	0.64	0.38	62.79
11/87	3	2.50	1.75	0.75	70.00
11/87	4	3.50	2.25	1.25	64.29
11/87	5	1.71	1.00	0.71	58.62
11/87	6	5.80	4.40	1.40	75.86
11/87	7	4.64	2.74	1.90	58.97
11/87	8	1.76	0.67	1.10	37.84
11/87	9	3.20	2.00	1.20	62.50
11/87	10	1.05	1.05	0.00	100.00
11/87	11	4.13	1.53	2.60	37.10
12/87	1	0.87	0.58	0.29	66.67
12/87	2	0.83	0.51	0.31	62.07
12/87	3	3.30	2.10	1.20	63.64
12/87	4	3.00	1.60	1.40	53.33
12/87	5	2.30	1.80	0.50	78.26
12/87	6	2.60	1.60	1.00	61.54
12/87	7	3.47	2.13	1.33	61.54
12/87	8	0.60	0.35	0.25	58.33
12/87	9	1.91	1.09	0.82	57.14
12/87	10	1.11	0.49	0.63	43.59
12/87	11	0.83	0.70	0.13	84.00
1/88	1	0.95	0.52	0.43	54.84
1/88	2	1.94	1.27	0.67	65.63
1/88	3	4.00	3.40	0.60	85.00
1/88	4	4.17	3.83	0.33	92.00
1/88	5	2.67	2.13	0.53	80.00
1/88	6	11.00	8.50	2.50	77.27
1/88	7	3.19	2.07	1.11	65.12
1/88	8	1.43	0.91	0.51	64.00
1/88	9	1.82	1.45	0.36	80.00
1/88	10	1.69	0.94	0.75	55.56
1/88	11	2.67	1.48	1.19	55.56

ULTRA-FINE PARTICULATE MATTER, ORGANIC AND INORGANIC FRACTIONS AND % ORGANICS (contd)

DATE	SITE	UFPM mg l-1	UFPOM mg l-1	UFPIM mg l-1	%ORG
8/86	1	0.70	0.60	0.10	85.71
8/86	2	1.40	1.20	0.20	85.71
8/86	3	3.80	2.20	1.60	57.89
8/86	4	3.40	2.20	1.20	64.71
8/86	5	3.50	1.80	1.70	51.43
8/86	6	6.80	5.20	1.60	76.47
8/86	7	9.20	3.40	5.80	36.96
8/86	8	0.80	0.80	0.00	100.00
8/86	9	14.40	5.20	9.20	36.11
8/86	10	10.60	4.60	6.00	43.40
8/86	11	7.40	2.60	4.80	35.14
9/86	1	0.80	0.60	0.20	75.00
9/86	2	1.04	0.40	0.64	38.46
9/86	3	3.80	1.80	2.00	47.37
9/86	4	6.10	3.80	2.30	62.30
9/86	5	2.73	1.00	1.73	36.63
9/86	6	6.00	2.40	3.60	40.00
9/86	7	5.33	2.00	3.33	37.52
9/86	8	1.07	0.67	0.40	62.62
9/86	9	13.80	5.00	8.80	36.23
9/86	10	5.60	3.73	1.87	66.61
9/86	11	6.30	3.80	2.50	60.32
10/86	1	0.77	0.50	0.27	64.94
10/86	2	1.14	0.86	0.28	75.44
10/86	3	2.75	1.25	1.50	45.45
10/86	4	2.40	1.20	1.20	50.00
10/86	5	3.00	1.90	1.10	63.33
10/86	6	24.00	9.16	14.84	38.17
10/86	7	7.40	2.60	4.80	35.14
10/86	8	ERR	ERR	0.00	ERR
10/86	9	5.84	2.15	3.69	36.82
10/86	10	2.67	1.20	1.47	44.94
10/86	11	2.73	1.13	1.60	41.39

DATE	SITE	UFPM mg l-1	UFPOM mg l-1	UFPIM mg l-1	%ORG
5/87	1	0.38	0.36	0.02	94.74
5/87	2	0.15	0.15	0.00	100.00
5/87	3	12.40	5.00	7.40	40.32
5/87	4	12.50	3.50	9.00	28.00
5/87	5	6.80	1.60	5.20	23.53
5/87	6	5.36	2.55	2.81	47.57
5/87	7	10.15	3.85	6.30	37.93
5/87	8	0.90	0.60	0.30	66.67
5/87	9	69.67	10.67	59.00	15.32
5/87	10	15.73	3.47	12.26	22.06
5/87	11	9.80	2.60	7.20	26.53
6/87	1	0.03	0.03	0.00	100.00
6/87	2	0.23	0.23	0.00	100.00
6/87	3	2.63	1.16	1.47	44.11
6/87	4	2.83	1.20	1.63	42.40
6/87	5	2.46	1.18	1.28	47.97
6/87	6	3.82	1.82	2.00	47.64
6/87	7	5.22	0.98	4.24	18.77
6/87	8	4.10	0.90	3.20	21.95
6/87	9	6.51	1.16	5.35	17.82
6/87	10	2.46	0.80	1.66	32.52
6/87	11	5.73	1.46	4.27	25.48
7/87	1	0.13	0.13	0.00	100.00
7/87	2	0.87	0.23	0.64	26.44
7/87	3	2.24	1.52	0.72	67.86
7/87	4	2.60	1.30	1.30	50.00
7/87	5	1.00	1.00	0.00	100.00
7/87	6	2.75	1.50	1.25	54.55
7/87	7	2.07	1.00	1.07	48.31
7/87	8	0.33	0.30	0.03	90.91
7/87	9	2.76	1.03	1.73	37.32
7/87	10	2.05	0.90	1.15	43.90
7/87	11	1.92	0.92	1.00	47.92

DATE	SITE	UFPM mg l-1	UFPOM mg l-1	UFPIM mg l-1	%ORG
2/88	1	0.36	0.36	0.00	100.00
2/88	2	2.70	2.10	0.60	77.78
2/88	3	12.55	7.45	5.09	59.42
2/88	4	4.89	4.44	0.44	90.91
2/88	5	6.14	3.57	2.57	58.14
2/88	6	33.50	12.50	21.00	37.31
2/88	7	5.00	2.92	2.08	58.33
2/88	8	2.82	1.91	0.91	67.74
2/88	9	7.20	3.00	4.20	41.67
2/88	10	7.07	2.27	4.80	32.08
2/88	11	4.17	1.83	2.35	43.75
3/88	1	0.32	0.32	0.00	100.00
3/88	2	0.91	0.86	0.06	93.75
3/88	3	4.27	2.53	1.73	59.37
3/88	4	3.00	1.75	1.25	58.33
3/88	5	2.34	2.26	0.09	96.30
3/88	6	8.40	6.80	1.60	80.95
3/88	7	2.32	1.60	0.72	68.97
3/88	8	1.22	1.22	0.00	100.00
3/88	9	5.82	4.36	1.45	75.00
3/88	10	3.84	3.04	0.80	79.17
3/88	11	2.14	1.36	0.77	63.83
4/88	1	0.17	0.17	0.00	100.00
4/88	2	0.37	0.23	0.13	63.64
4/88	3	6.40	2.40	4.00	37.50
4/88	4	5.00	2.74	2.26	54.84
4/88	5	3.45	1.91	1.55	55.26
4/88	6	3.68	3.68	0.00	100.00
4/88	7	1.73	1.00	0.73	57.89
4/88	8	0.74	0.74	0.00	100.00
4/88	9	13.06	6.67	6.39	51.06
4/88	10	16.83	1.98	14.85	11.76
4/88	11	1.43	0.87	0.57	60.47

c) Macroinvertebrate drift data (refers to Paper III)

units = no. $100m^{-3}$

SITE PR1

DATE	Plecopt	Ephem	Trichopt	Simulid	Chirono	Ceratopog	Chaos	Empidid	Rhagion	Tabanid
4/86	0	0	0	0	0	0	0			
5/86		334	150	1521	1889	134	0		17	
8/86	ERR	ERR	ERR	ERR	ERR	ERR	ERR	ERR		
9/86	25	147	197	172	442		0			25
10/86	0	3952	101	554	1158	0	0			
11/86	0	1445	76	51	659	0	0			
12/86		0	0	0	111		0		0	
1/87	114	0	0	0	114	0	0		0	
4/87		531	250	0	1780	0	31			
6/87	0	0		0	213		0			
8/87	0	87		144	318	0		0		
10/87	0	1577	0	707	1632	0				
12/87		5631	0	67	4357		0		0	
2/88		ERR	ERR	ERR	ERR		ERR			
4/88	621	23	0	230	2368		0		23	

DATE	Ephydrid	Oligo	Nematod	Triclads	u'necta	Hemipt	Gerrid	Hydraen	Helodid	Elmid-A
4/86		0	0	0	0				0	0
5/86		167	17	134	0			0	33	0
8/86		ERR	ERR		ERR			ERR	ERR	ERR
9/86		98	0		0			0		
10/86	25	126	0		0			25		50
11/86		228	0	0	0				0	51
12/86		111	0	0	0				0	
1/87		456	0	0	0					0
4/87		0	0	0						
6/87		0	0		0			0		
8/87		43	58		0			29	29	
10/87		0	0		0		0			0
12/87		34	0	0	0	0		268	268	268
2/88		ERR	ERR	ERR	ERR				ERR	
4/88		1172	0	0					0	

DATE	Elmid-B	Elmid-C	Dryopid	Dyticid	Coleo'ad	Aeshnid	Gomphid	Lepidopt	Megalopt	Copepod
4/86		0			0	1000			0	0
5/86		418			0	0			0	0
8/86		ERR							ERR	ERR
9/86										0
10/86				25	25			0	0	0
11/86		51			0	0		0		0
12/86		0				0		0		0
1/87		0								0
4/87		31					0			500
6/87					0					267
8/87		14	0					0		116
10/87	0	54								326
12/87		302			0					1341
2/88		ERR	ERR							ERR
4/88		23				0			0	207

DATE	Cladoc	Nauplii	Ostracod	Amphi	H'carina	Collem	Lymnea	FerrissiaRotifers	Hydra
4/86	0		0		0	0			0
5/86	0		0		17				0
8/86	ERR		ERR		ERR	ERR			ERR
9/86	0		0		49	25			0
10/86	0		0		25				0
11/86	0		0	0	101				0
12/86	0		0		56			0	0
1/87	0		0		0				0
4/87	0		0		0	0			0
6/87	107	0	0		0	53	0		0
8/87	29		0	0	87	14			0
10/87	109				0				0
12/87	335			134	268		0	0	0
2/88	ERR				ERR				ERR
4/88	0		0		0		0		0

SITE PR2

DATE	Plecopt	Ephem	Trichopt	Simulid	Chirono	Ceratopog	Chaos	Empidid	Rhagion	Tabanid
4/86	0	0	0	0	0	0	0			
5/86		272	0	136	5959	0	0		0	
8/86	74	180	11	138	1847	64	0	32		
9/86	0	0	0	0	0		0			0
10/86	84	1597	252	504	6977	84	0			
11/86	42	4686	669	1674	21150	335	335			
12/86		570	44	66	2237		307		22	
1/87	0	282	0	752	1850	0	0		0	
4/87		244	0	244	9041	0	0			
6/87	0	84		63	1012		0			
8/87	0	139		60	5082	40		0		
10/87	0	860	0	0	0	0				
12/87		298	0	0	2761		15		0	
2/88		155	0	1759	2587		0			
4/88	0	197	0	1973	2920		0		0	

DATE	Ephydrid	Oligo	Nematod	Triclads	u'necta	Hemipt	Gerrid	Hydraen	Helodid	Elmid-A
4/86		0	0	0	0				0	0
5/86		1805	153	0	0			0	0	136
8/86		340	117		21			21	0	11
9/86		0	0		0			0		
10/86	0	756	84		0			84		0
11/86		5355	0	0	0				0	0
12/86		614	88	0	88				0	
1/87		251	0	0	0					0
4/87		2688	244	0						
6/87		485	0		0			21		
8/87		258	139		0			0	0	
10/87		0	0		860		0			0
12/87		1388	119	0	0	0		0	0	119
2/88		1397	103	0	0				0	
4/88		1598	316	0					0	

DATE	Elmid-B	Elmid-C	Dryopid	Dyticid	Coleo'ad	Aeshnid	Gomphid	Lepidopt	Megalopt	Copepod
4/86		0			0	0			0	0
5/86		0			0	0			0	0
8/86		0							0	64
9/86										0
10/86				0	0			0	0	0
11/86		0			0	0		0		1339
12/86		0				22		0		197
1/87		0								251
4/87		244					0			733
6/87					0					21
8/87		0	0					20		278
10/87	0	0								0
12/87		0			15					2388
2/88		52	52							103
4/88		20				0			0	0

DATE	Cladoc	Nauplii	Ostracod	Amphi	H'carina	Collem	Lymnea	Ferrissia	Rotifers	Hydra
4/86	0		0		0	0				0
5/86	545		0		0					0
8/86	159		0		96	127				0
9/86	0		0		0	0				0
10/86	0		0		84					0
11/86	2343		0	0	0					0
12/86	8377		0		66				2390	241
1/87	1756		0		0					0
4/87	0		0		0	489				0
6/87	21	0	0		21	42	0			0
8/87	159		0	218	20	20				0
10/87	0				0					0
12/87	14698			0	119		0	0		0
2/88	0				0					414
4/88	1263		0		0		0			0

SITE PR3

DATE	Plecopt	Ephem	Trichopt	Simulid	Chirono	Ceratopog	Chaos	Empidid	Rhagion	Tabanid
4/86	1000	1000	0	0	4000	1000	16000			
5/86		17	17	0	1059	0	5776		0	
8/86	19	0	0	0	253	0	272	0		
9/86	0	0	0	0	246		1116			0
10/86	0	0	0	0	500	0	217			
11/86	0	277	0	0	1404	0	5825			
12/86		0	0	0	253		4979		17	
1/87	0	0	0	0	678	0	4307		0	
4/87		0	0	174	3314	0	916			
6/87	0	0		32	226		32			
8/87	0	0		14	0	0		0		
10/87	ERR	ERR	ERR	ERR	ERR	ERR				
12/87		27	14	0	1536		4155		0	
2/88		0	0	0	483		8364			
4/88	0	406	0	76	3528		4112		0	

DATE	Ephydrid	Oligo	Nematod	Triclads	u'necta	Hemipt	Gerrid	Hydraen	Helodid	Elmid-A
4/86		2000	2000	0	2000				0	0
5/86		17	0	0	0			0	0	0
8/86		58	58		0			0	0	0
9/86		0	0		0			22		
10/86	0	522	22		0			0		0
11/86		5270	277	0	555				0	0
12/86		236	17	0	68				0	
1/87		113	0	0	0					0
4/87		0	0	0						
6/87		48	0		0			0		
8/87		0	0		0			0	0	
10/87		ERR	ERR		ERR		ERR			ERR
12/87		14	14	0	0	0		0	0	0
2/88		0	0	0	0				0	
4/88		0	0	0					0	

DATE	Elmid-B	Elmid-C	Dryopid	Dyticid	Coleo'ad	Aeshnid	Gomphid	Lepidopt	Megalopt	Copepod
4/86		0			0	0			0	102000
5/86		0			0	0			0	9193
8/86		0							0	10639
9/86										1139
10/86				0	0			0	0	45766
11/86		0			0	0		0		10263
12/86		0				0		0		8726
1/87		0								14122
4/87		0					0			69824
6/87					0					5263
8/87		0	0					0		8852
10/87	ERR	ERR								ERR
12/87		0			0					33435
2/88		0	0							17520
4/88		0				0			0	35132

DATE	Cladoc	Nauplii	Ostracod	Amphi	H'carina	Collem	Lymnea	Ferrissia	Rotifers	Hydra
4/86	26000		0		0	1000				0
5/86	666		0		0					51
8/86	9588		0		39	0				0
9/86	3684		0		22	0				0
10/86	95075		0		0					522
11/86	198611		0	0	0					1942
12/86	40779		0		51				0	0
1/87	7188		0		0					0
4/87	8197		0		174	0				8197
6/87	2745	13707	0		32	0	0			0
8/87	1521		0	0	0	0				0
10/87	ERR				ERR					ERR
12/87	220471			0	0		0	0		0
2/88	73444				0					0
4/88	150681		0		0		0			1878

SITE PR4

DATE	Plecopt	Ephem	Trichopt	Simulid	Chirono	Ceratopog	Chaos	Empidid	Rhagion	Tabanid
4/86	0	2000	1000	0	800000	0	8000			
5/86		0	0	0	1258	0	50		0	
8/86	0	0	60	0	6440	60	0	0		
9/86	1008	0	0	504	6804		504			0
10/86	0	0	0	0	1914	0	46			
11/86	0	0	0	0	4560	0	568			
12/86		0	23	0	2199		374		0	
1/87	0	0	18	0	3857	18	0		0	
4/87		0	320	320	55290	0	0			
6/87	0	0		50	586		17			
8/87	0	0		65	697	22		0		
10/87	0	0	0	947	3581	0				
12/87		0	0	18	17358		1568		0	
2/88		0	0	0	17780		25986			
4/88	0	0	31	246	15722		0		0	

DATE	Ephydrid	Oligo	Nematod	Triclads	u'necta	Hemipt	Gerrid	Hydraen	Helodid	Elmid-A
4/86		1000	0	0	0				0	0
5/86		67	0	0	0			0	0	0
8/86		239	298		0			0	0	0
9/86		63	504		0			0		
10/86	0	92	0		92			0		0
11/86		3407	35	0	0				0	284
12/86		702	140	0	117				0	
1/87		0	0	0	0					0
4/87		0	0	0						
6/87		50	34		0			0		
8/87		458	65		0			0	0	
10/87		0	0		0		0			0
12/87		0	0	0	0	0		0	0	0
2/88		0	0	0	456				0	
4/88		0	0	0					31	

DATE	Elmid-B	Elmid-C	Oryopid	Dyticid	Coleo'ad	Aeshnid	Gomphid	Lepidopt	Megalopt	Copepod
4/86		0			0	0			0	31000
5/86		0			0	0			0	134
8/86		60							0	1550
9/86										83224
10/86				0	0			0	0	8903
11/86		0			0	0		0		1987
12/86		0				0		0		3416
1/87		0								148
4/87		0					0			13743
6/87					0					31963
8/87		0	0					22		54789
10/87	0	0								358887
12/87		0			0					77822
2/88		0	0							29634
4/88		15				0			0	0

DATE	Cladoc	Nauplii	Ostracod	Amphi	H'carina	Collem	Lymnea	FerrissiaRotifers	Hydra
4/86	18000		0		4000	0			9000
5/86	117		0		0				185
8/86	2087		0		119	0			0
9/86	283755		0		0	0			0
10/86	1984		0		0				46
11/86	4827		0	0	0				0
12/86	8914		0		117			0	117
1/87	3100		0		0				0
4/87	0		0		0	0			3835
6/87	670	17221	0		0	0	0		0
8/87	13120		0	0	0	0			0
10/87	34558				1294				0
12/87	574094			0	0		0	0	0
2/88	34193				0				0
4/88	492		0		0		0		385

SITE PR5

DATE	Plecopt	Ephem	Trichopt	Simulid	Chirono	Ceratopog	Chaos	Empidid	Rhagion	Tabanid
4/86	0	0	4000	0	19000	0	2000			
5/86		0	0	0	0	0	0		0	
8/86	0	0	0	0	36	0	0	0		
9/86	0	0	0	0	124		0			0
10/86	52	104	0	0	597	0	0			
11/86	0	99	0	0	771	0	0			
12/86		51	0	0	734		0		0	
1/87	0	0	0	0	375	0	54		0	
4/87		0	0	40	1130	0	0			
6/87	0	0		0	209		0			
8/87	0	44		29	790	88		0		
10/87	0	39	0	750	0	0				
12/87		57	0	0	1142		57		0	
2/88		44	0	0	888		0			
4/88	0	104	0	0	521		0		0	

DATE	Ephydrid	Oligo	Nematod	Triclads	u'necta	Hemipt	Gerrid	Hydraen	Helodid	Elmid-A
4/86		0	0	0	0				0	0
5/86		0	0	0	0			0	0	0
8/86		0	0		0			0	0	0
9/86		41	0		0			0		
10/86	0	78	26		0			26		0
11/86		50	124	0	0				0	0
12/86		228	51	0	0				25	
1/87		0	0	0	0					0
4/87		40	0	0						
6/87		52	0		0			0		
8/87		425	146		15			0	0	
10/87		0	39		0		0			0
12/87		57	0	0	0	0		0	0	57
2/88		44	22	0	22				0	
4/88		0	104	0					0	

DATE	Elmid-B	Elmid-C	Dryopid	Dyticid	Coleo'ad	Aeshnid	Gomphid	Lepidopt	Megalopt	Copepod
4/86		0			0	0			1000	0
5/86		0			0	0			0	0
8/86		0							0	680
9/86										138
10/86				0	26			0	26	441
11/86		0			25	0		0		174
12/86		25				0		0		152
1/87		54								0
4/87		0					0			0
6/87					0					314
8/87		29	0					15		26232
10/87	0	0								158
12/87		29			0					571
2/88		0	0							0
4/88		0				0			0	52

DATE	Cladoc	Nauplii	Ostracod	Amphi	H'carina	Collem	Lymnea	FerrissiaRotifers	Hydra
4/86	0		0		2000	0			0
5/86	0		0		0				0
8/86	251		0		72	0			0
9/86	730		0		0	0			0
10/86	363		0		0				0
11/86	274		0	0	99				0
12/86	658		0		51			0	0
1/87	0		0		0				161
4/87	363		0		0	0			40
6/87	262	0	0		105	0	0		0
8/87	688		0	0	29	59			0
10/87	828				0				0
12/87	2370			0	29		0	0	0
2/88	0				0				0
4/88	52		0		0		0		0

SITE PR7

DATE	Plecopt	Ephem	Trichopt	Simulid	Chirono	Ceratopog	Chaos	Empidid	Rhagion	Tabanid
4/86	1000	0	1000	0	11000	1000	1000			
5/86		99	0	99	395	0	0		0	
8/86	0	0	0	0	766	0	0	0		
9/86	ERR	ERR	ERR	ERR	ERR		ERR			ERR
10/86	0	274	0	84	4784	0	0			
11/86	0	293	33	65	991	0	0			
12/86		450	144	90	2198		0		0	
1/87	0	17	133	83	663	0	0		0	
4/87		38	0	0	38	13	13			
6/87	0	0		66	263		0			
8/87	0	0		0	0	0		0		
10/87	0	78	0	0	831	0				
12/87		172	0	459	5275		0		0	
2/88		0	0	631	50468		0			
4/88	0	109	0	0	164		109		0	

DATE	Ephydrid	Oligo	Nematod	Triclads	u'necta	Hemipt	Gerrid	Hydraen	Helodid	Elmid-A
4/86		34000	0	1000	0				0	0
5/86		0	198	0	0			0	0	0
8/86		1602	70		0			0	0	0
9/86		ERR	ERR		ERR			ERR		
10/86	0	1011	179		0			0		0
11/86		293	16	33	1105				0	0
12/86		0	144	0	432				0	
1/87		265	0	0	1193					0
4/87		25	0	0						
6/87		0	0		33			0		
8/87		0	0		0			0	0	
10/87		831	0		0		0			0
12/87		0	0	115	1376	0		0	57	0
2/88		0	631	631	0				0	
4/88		0	821	0					0	

DATE	Elmid-B	Elmid-C	Dryopid	Oyticid	Coleo'ad	Aeshnid	Gomphid	Lepidopt	Megalopt	Copepod
4/86		0			0	0			1000	94000
5/86		0			0	198			0	3460
8/86		0							0	4039
9/86										ERR
10/86				0	0			0	0	1180
11/86		0			0	0		0		1463
12/86		0				0		0		1009
1/87		0								0
4/87		0					0			4195
6/87					0					88348
8/87		0	0					0		0
10/87	0	0								359723
12/87		115			0					2638
2/88		0	0							170960
4/88		0				0			0	1150

DATE	Cladoc	Nauplii	Ostracod	Amphi	H'carina	Collem	Lymnea	Ferrissia	Rotifers	Hydra
4/86	38000		1000		1000	0				6000
5/86	60297		0		0					0
8/86	1602		0		139	70				209
9/86	ERR		ERR		ERR	ERR				ERR
10/86	590		0		0					84
11/86	3120		49	0	0					81
12/86	2738		144		0				0	0
1/87	1459		928		0					0
4/87	0		1105		0	0				0
6/87	46015	69153	0		33	0	0			0
8/87	0		0	0	0	0				0
10/87	136413				91					0
12/87	344			0	0		344	57		0
2/88	649773				0					4416
4/88	1314		3668		493		55			0

SITE PR8

DATE	Plecopt	Ephem	Trichopt	Simulid	Chirono	Ceratopog	Chaos	Empidid	Rhagion	Tabanid
4/86	0	0	0	2000	18000	0	0			
5/86		210	9	630	6589	0	0		0	
8/86	0	17	17	17	618	0	0	0		
9/86	0	27	0	0	353		0			0
10/86	0	45	113	0	928	0	0			
11/86	0	3958	918	2782	22543	0	229			
12/86		ERR	ERR	ERR	ERR		ERR		ERR	
1/87	0	239	48	1959	717	0	0		0	
4/87		0	11	11	199	0	0			
6/87	ERR	ERR		ERR	ERR		ERR			
8/87	37	19		0	859	0		9		
10/87	63	106	0	42	1395	21				
12/87		58	39	58	504		0		0	
2/88		243	0	0	364		0			
4/88	50	100	0	2496	1697		0		0	

DATE	Ephydrid	Oligo	Nematod	Triclads	u'necta	Hemipt	Gerrid	Hydraen	Helodid	Elmid-A
4/86		1000	2000	0	0				0	14000
5/86		88	0	0	70			0	0	0
8/86		17	0		0			0	0	0
9/86		27	0		0			0		
10/86	0	0	0		45			0		0
11/86		459	229	0	229				229	14
12/86		ERR	ERR	ERR	ERR				ERR	
1/87		812	48	0	48					0
4/87		0	0	0						
6/87		ERR	ERR		ERR			ERR		
8/87		47	56		9			19	0	
10/87		21	0		0		0			0
12/87		0	0	0	0	0		0	19	19
2/88		0	0	0	0				121	
4/88		100	0	50					0	

DATE	Elmid-B	Elmid-C	Dryopid	Dyticid	Coleo'ad	Aeshnid	Gomphid	Lepidopt	Megalopt	Copepod
4/86		2000			1000	0			0	15000
5/86		0			0	140			0	1470
8/86		0							0	0
9/86										0
10/86				0	0			0	0	23
11/86		14			14	14		229		688
12/86		ERR				ERR		ERR		ERR
1/87		0								334
4/87		0					0			33
6/87					ERR					ERR
8/87		0	0					0		308
10/87	0	85								0
12/87		78			39					291
2/88		0	0							243
4/88		399				0			0	2795

DATE	Cladoc	Nauplii	Ostracod	Amphi	H'carina	Collem	Lymnea	Ferrissia	Rotifers	Hydra
4/86	17000		0		9000	0				0
5/86	28422		0		560					0
8/86	34		0		69	0				0
9/86	27		0		14	0				0
10/86	45		45		91					0
11/86	6424		229	229	4130					0
12/86	ERR		ERR		ERR				ERR	ERR
1/87	1099		0		2054					48
4/87	232		0		11	0				0
6/87	ERR	ERR	ERR		ERR	ERR	ERR			ERR
8/87	289		9	0	93	47				0
10/87	106				0					21
12/87	369			0	136		0	0		0
2/88	121				364					0
4/88	7586		0		799		0			0

SITE PR9

DATE	Plecopt	Ephem	Trichopt	Simulid	Chirono	Ceratopog	Chaos	Empidid	Rhagion	Tabanid
4/86	0	0	0	1000	16000	0	2000			
5/86		96	0	96	96	0	2377		0	
8/86	0	0	0	32	510	0	64	0		
9/86	0	11	0	0	452		1345			0
10/86	0	203	2439	10	274	0	152			
11/86	0	264	949	105	369	0	0			
12/86		ERR	ERR	ERR	ERR		ERR		ERR	
1/87	0	228	101	355	203	0	709		0	
4/87		39	309	348	16194	0	3324			
6/87	0	148		99	197		888			
8/87	0	0		34	34	0		0		
10/87	0	13961	0	0	365	0				
12/87		71	214	71	713		71		0	
2/88		215	388	0	861		86			
4/88	0	589	589	110	1987		6586		0	

DATE	Ephydrid	Oligo	Nematod	Triclads	u'necta	Hemipt	Gerrid	Hydraen	Helodid	Elmid-A
4/86		17000	0	0	0				0	0
5/86		0	0	21	0			0	0	0
8/86		0	0		0			0	0	0
9/86		357	0		0			0		
10/86	0	2591	0		0			0		0
11/86		1028	26	26	0				0	0
12/86		ERR	ERR	ERR	ERR				ERR	
1/87		760	304	25	51					0
4/87		116	0	271						
6/87		0	0		0			0		
8/87		0	0		0			0	0	
10/87		487	81		0		0			0
12/87		285	0	0	0	0		0	0	0
2/88		43	172	0	0				0	
4/88		625	0	37					0	

DATE	Elmid-B	Elmid-C	Dryopid	Dyticid	Coleo'ad	Aeshnid	Gomphid	Lepidopt	Megalopt	Copepod
4/86		0			0	0			0	1864000
5/86		0			0	0			0	23284
8/86		0							0	5772
9/86										4120
10/86				0	0			0	0	14481
11/86		0			0	0		0		3059
12/86		ERR				ERR		ERR		ERR
1/87		0								2406
4/87		0					0			3092
6/87					0					37488
8/87		0	0					0		17701
10/87	0	41								1055
12/87		0			0					285
2/88		0	0							0
4/88		0				0			0	35322

DATE	Cladoc	Nauplii	Ostracod	Amphi	H'carina	Collem	Lymnea	Ferrissia	Rotifers	Hydra
4/86	632000		0		0	0				0
5/86	61899		85		0					256
8/86	702		0		0	0				0
9/86	252		84		0	0				0
10/86	4227		0		0					325
11/86	3666		0	0	26					237
12/86	ERR		ERR		ERR				ERR	ERR
1/87	1342		0		0					0
4/87	928		0		0	0				0
6/87	17955	89182	148		49	49	0			0
8/87	38653		0	0	0	0				0
10/87	3896				0					203
12/87	3068			0	0		143	71		214
2/88	0				0					0
4/88	4121		0		0		0			0

SITE PR10

DATE	Plecopt	Ephem	Trichopt	Simulid	Chirono	Ceratopog	Chaos	Empidid	Rhagion	Tabanid
4/86	0	0	0	0	0	0	0			
5/86		122	0	340	897	0	0		14	
8/86	0	0	0	0	411	0	0	0		
9/86	0	0	0	0	0		0			0
10/86	0	0	0	0	0	0	0			
11/86	0	0	0	0	0	0	0			
12/86		ERR	ERR	ERR	ERR		ERR		ERR	
1/87	0	140	87	506	3158	0	0		0	
4/87		ERR	ERR	ERR	ERR	ERR	ERR			
6/87	17	34		120	684		0			
8/87	0	0		45	59	0		0		
10/87	0	0	21	0	1254	0				
12/87		456	942	182	9239		0		30	
2/88		71	0	0	2997		0			
4/88	0	0	0	343	815		0		0	

DATE	Ephydrid	Oligo	Nematod	Triclads	u'necta	Hemipt	Gerrid	Hydraen	Helodid	Elmid-A
4/86		0	0	0	0				0	0
5/86		0	0	0	0			0	0	0
8/86		44	117		0			0	0	0
9/86		0	0		0			0		
10/86	0	0	0		0			0		0
11/86		0	0	0	0				0	0
12/86		ERR	ERR	ERR	ERR				ERR	
1/87		35	0	0	35					0
4/87		ERR	ERR	ERR						
6/87		0	17		0			0		
8/87		30	45		0			0	0	
10/87		170	0		0		0			0
12/87		942	0	0	0	182		0	0	0
2/88		0	143	0	0				0	
4/88		14	0	14					0	

DATE	Elmid-B	Elmid-C	Dryopid	Dyticid	Coleo'ad	Aeshnid	Gomphid	Lepidopt	Megalopt	Copepod
4/86		0			0	0			0	0
5/86		0			0	0			14	1522
8/86		0							0	11860
9/86										0
10/86				0	0			0	0	0
11/86		0.			0	0		0		0
12/86		ERR				ERR		ERR		ERR
1/87		0								140
4/87		ERR					ERR			ERR
6/87					17					5622
8/87		0	0					0		104501
10/87	0	0								235427
12/87		30			30					182
2/88		0	0							0
4/88		14				14			14	5832

DATE	Cladoc	Nauplii	Ostracod	Amphi	H'carina	Collem	Lymnea	Ferrissia	Rotifers	Hydra
4/86	1000		0		0	0				0
5/86	4457		0		0					1223
8/86	470		0		0	0				0
9/86	0		0		0	0				0
10/86	0		0		0					0
11/86	0		0	0	0					0
12/86	ERR		ERR		ERR				ERR	ERR
1/87	488		70		70					35
4/87	ERR		ERR		ERR	ERR				ERR
6/87	444	68	17		17	0	17			51
8/87	62225		0	0	0	0				45
10/87	17464				0					2061
12/87	851			0	61		0	0		61
2/88	0				0					0
4/88	800		0		0		0			0

SITE PR11

DATE	Plecopt	Ephem	Trichopt	Simulid	Chirono	Ceratopog	Chaos	Empidid	Rhagion	Tabanid
4/86	0	1000	0	1000	2000	0	0			
5/86		207	0	827	451	0	0		0	
8/86	0	53	0	79	934	79	0	0		
9/86	0	0	0	0	0		0			0
10/86	72	865	0	396	3513	0	0			
11/86	0	0	59	234	644	0	0			
12/86		124	50	124	347		0		0	
1/87	0	204	20	285	102	0	41		41	
4/87		2284	623	0	30111	0	208			
6/87	17	0		116	1296		0			
8/87	ERR	ERR		ERR	ERR	ERR		ERR		
10/87	ERR	ERR	ERR	ERR	ERR	ERR				
12/87		107	0	321	285		0		0	
2/88		410	23	410	593		0			
4/88	0	28	28	56	306		28		0	

DATE	Ephydrid	Oligo	Nematod	Triclads	u'necta	Hemipt	Gerrid	Hydraen	Helodid	Elmid-A
4/86		0	0	0	0				1000	0
5/86		100	6	0	0			50	0	0
8/86		487	53		0			0	0	0
9/86		0	0		0			0		
10/86	0	775	72		0			0		18
11/86		0	0	0	0				0	0
12/86		25	25	0	0				0	
1/87		20	0	0	20					20
4/87		2284	415	0						
6/87		349	17		0			17		
8/87		ERR	ERR		ERR			ERR	ERR	
10/87		ERR	ERR		ERR		ERR			ERR
12/87		36	0	0	71	0		0	0	36
2/88		91	0	0	0				91	
4/88		83	0	0					0	

DATE	Elmid-B	Elmid-C	Dryopid	Dyticid	Coleo'ad	Aeshnid	Gomphid	Lepidopt	Megalopt	Copepod
4/86		0			0	0			0	1000
5/86		13			6	0			0	150
8/86		0							0	1053
9/86										0
10/86				0	0			72	0	288
11/86		0			0	0		0		0
12/86		0				0		0		50
1/87		0								20
4/87		0					208			1454
6/87					0					565
8/87		ERR	ERR					ERR		ERR
10/87	ERR	ERR								ERR
12/87		0			0					321
2/88		0	0							91
4/88		0				0			0	28

DATE	Cladoc	Nauplii	Ostracod	Amphi	H'carina	Collem	Lymnea	FerrissiaRotifers	Hydra
4/86	0		0		1000	0			0
5/86	451		0		0				0
8/86	132		53		53	0			0
9/86	0		0		0	0			0
10/86	0		36		0				0
11/86	0		0	0	703				0
12/86	50		0		0			0	0
1/87	305		0		61				0
4/87	76419		0		208	1246			0
6/87	598	33	17		17	0	0		0
8/87	ERR		ERR	ERR	ERR	ERR			ERR
10/87	ERR				ERR				ERR
12/87	356			0	71		0	0	0
2/88	1458				0				0
4/88	445		0		0		0		0

d) **Benthic macroinvertebrate data (refers to Paper IV)**

units = no. m^{-2}

PR1 (no.m-2)

Date	4/88			2/88			12/87			10/87			8/87			6/87			4/87			2/87	
Replicate	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B2	B3
Plecoptera	840	220	300	390	80	0	670	400	30	90	230	0	750	550	0	10	20	0	70	30	0	10	0
Ephemeroptera	1240	1670	300	550	20	10	450	1050	240	300	660	1200	240	770	30	720	380	380	2780	1460	10	170	80
Simulidae	190	0	0	570	590	70	0	0	10	40	20	80	150	290	50	20	50	0	180	40	20	0	10
Chironomidae	2390	2590	0	30	0	10	1030	1270	120	560	1520	90	260	310	60	230	40	90	2270	1020	200	1250	160
Rhagionidae	310	250	0	190	10	0	190	50	30	0	30	0	0	10	0	0	0	0	40	10	0	10	0
Ceratopogonidae	0	10	0	0	0	0	0	10	10	40	0	0	0	0	0	0	0	0	40	0	10	0	0
Empididae																							
Tabanidae																							
Tipulidae																							
Chaoboridae																							
Blephariceridae	0	0	0	0	0	0	0	10	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0
Culicidae																							
Megaloptera	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	10	0	0	10	0
Trichoptera	0	10	0	70	0	0	0	60	80	10	50	150	0	0	0	460	40	120	60	80	20	90	10
Lepidoptera																							
Coleoptera (ad)	260	10	40	300	60	10	10	60	40	0	100	0	0	0	0	0	0	0	20	20	0	0	0
Helodidae	20	0	0	140	100	10	20	30	0	60	130	0	10	80	0	120	110	0	160	80	0	50	10
Elmidae-A	10	0	60	0	0	0	0	0	0	40	0	20	0	90	10	20	0	0	10	0	10	0	10
Elmidae-B																							
Elmidae-C	520	650	120	0	0	0	180	130	20	130	60	0	10	10	0	70	50	10	400	240	30	650	20
Corixidae																							
Gerridae																							
Hydraenidae	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hydrophilidae																							
Hydroptilidae	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dyticidae																							
Belastomatidae																							
Hemiptera																							
Notonectidae																							
Naucorridae																							
Hebridae																							
Aeshnidae	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0
Gomphidae																							
Zygoptera	0	0	0	30	0	0	0	0	0	60	0	0	0	0	0	0	0	0	0	0	0	0	0
Hydracarina	80	0	0	0	0	0	160	160	10	120	200	0	0	20	0	30	0	20	0	80	0	0	0
Oligochaeta	360	200	0	0	0	0	0	300	30	70	160	0	0	10	0	0	70	0	100	100	20	180	0
Nematoda	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	40	40	0	0	0
Tricladida	0	0	0	0	0	0	0	40	0	0	60	0	0	0	0	0	0	0	50	0	0	0	0
Nematomorpha																							
Hirudinea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0
Hydra																							
Ostracoda	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0
Amphipoda	0	10	0	40	0	0	20	60	0	0	30	0	0	0	0	0	0	0	20	0	0	70	0
Isopoda																							
Decapoda																							
Mollusca																							
Collembola	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0
Anthomyidae																							
Rotatoria																							

PR2 (no.m-2)

Date	4/88			2/88			12/87			10/87			8/87			6/87			4/87			2/87		
Replicate	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3
Plecoptera	540	150	50	10	30	30	10	30	30	0	0	0	0	0	0	40	20	0	0	40	0	0	0	160
Ephemeroptera	570	900	930	1180	1280	1780	2470	830	2010	0	0	0	80	50	100	200	50	790	580	1210	640	2460	800	2800
Simulidae	3560	790	10760	70	90	90	1520	290	630	0	0	0	1050	20	40	610	460	0	0	1100	70	90	0	720
Chironomidae	4230	2240	5500	2890	3530	5370	2220	1220	4860	0	60	160	2650	2590	1990	1240	1300	5440	5740	8640	3260	2090	1040	7120
Rhagionidae	30	10	10	30	40	10	90	0	10	0	0	0	10	0	0	20	20	0	0	10	0	0	0	80
Ceratopogonidae	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0	10	30	80	160	160	110	0	0	80
Empididae	0	0	0	0	0	0	0	170	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0
Tabanidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	160
Tipulidae																								
Chaoboridae	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Blephariceridae																								
Culicidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	0	0	0	0
Megaloptera	20	30	0	40	70	30	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0
Trichoptera	40	390	40	190	360	140	190	0	110	0	0	0	20	0	10	0	0	10	90	170	20	250	1280	2560
Lepidoptera																								
Coleoptera (ad)	380	50	100	60	20	120	30	0	20	0	60	0	0	0	0	30	10	0	0	40	0	100	0	0
Helodidae	10	20	0	20	70	0	140	10	0	0	0	0	0	0	0	20	10	0	80	0	0	120	280	240
Elmidae-A	20	50	70	60	40	200	10	0	0	0	0	0	0	0	0	0	0	10	0	0	0	40	120	80
Elmidae-B	0	0	0	10	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Elmidae-C	200	420	100	160	350	220	1050	100	520	10	10	0	20	0	40	550	130	0	80	20	20	690	2160	2880
Corixidae	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gerridae	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
Hydraenidae	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0
Hydrophilidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0
Hydroptilidae																								
Dyticidae																								
Belastomatidae																								
Hemiptera	0	0	10	0	10	0	0	0	10	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0
Notonectidae	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Naucorridae																								
Hebridae																								
Aeshnidae	0	10	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	40	0
Gomphidae	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	20	0	0	0
Zygoptera	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hydracarina	0	0	0	80	40	60	0	0	20	0	0	0	0	0	300	30	30	0	240	240	0	220	80	320
Oligochaeta	4170	2620	8100	680	500	300	8320	9230	12320	20	0	0	1090	20	200	220	30	0	10090	3390	810	100	760	4560
Nematoda	430	720	520	0	0	0	0	0	0	10	0	0	10	10	110	50	10	170	640	3070	600	160	2320	4000
Tricladida	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nematomorpha																								
Hirudinea																								
Hydra	0	0	0	10	10	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ostracoda	320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amphipoda																								
Isopoda																								
Decapoda																								
Mollusca																								
Collembola	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	10	0	0	240	170	0	0	0	0
Anthomyidae																								
Rotatoria																								

PR4 (no.m-2)

Date	4/88			2/88			12/87			10/87			6/87			4/87			2/87		
Replicate	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3
Plecoptera	40	0	0	960	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	120	0
Ephemeroptera	40	80	0	1920	320	960	80	320	0	0	40	200	80	40	80	0	120	320	320	240	320
Simulidae	80	0	0	0	0	0	0	0	0	0	0	0	0	140	250	80	80	0	0	490	0
Chironomidae	14120	99520	42550	434880	284480	433920	40880	61200	114720	55040	51560	98360	770	6370	23930	36040	39280	217720	183280	16990	238080
Rhagionidae	0	0	0	320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceratopogonidae	0	0	0	0	0	0	0	160	0	0	0	40	0	0	0	0	0	0	0	80	0
Empididae	40	0	0	0	0	0	0	0	160	0	0	0	0	0	0	0	0	0	0	0	0
Tabenidae																					
Tipulidae	0	0	0	320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chaoboridae	0	0	0	320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Blephariceridae																					
Culicidae																					
Megaloptera	0	0	0	320	0	320	0	160	0	0	0	0	0	0	0	0	0	40	0	0	0
Trichoptera	700	640	80	160	160	0	80	0	1920	50	200	360	260	440	2210	480	640	3920	0	1770	1600
Lepidoptera																					
Coleoptera (ad)	0	0	0	0	0	0	0	0	320	80	0	80	0	20	20	0	0	40	0	0	0
Helodidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	160	0	0	0
Elmidae-A	80	80	0	0	0	0	160	640	0	0	0	0	0	10	250	40	60	800	1360	30	640
Elmidae-B																					
Elmidae-C	0	0	0	320	320	0	80	0	0	0	0	40	0	0	20	0	100	360	320	0	960
Corixidae	0	0	0	0	0	320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gerridae																					
Hydraenidae																					
Hydrophilidae																					
Hydroptilidae																					
Dyticidae																					
Belastomatidae																					
Hemiptera																					
Notonectidae																					
Naucorridae																					
Hebridae																					
Aeshnidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	0	0	0	0
Gomphidae																					
Zygoptera																					
Hydracarina	240	2000	10	2240	5760	3840	80	80	160	0	0	440	40	170	400	200	760	1920	2560	280	1600
Oligochaeta	40	0	0	1920	640	10560	240	0	0	0	40	100	0	0	0	320	880	80	0	280	0
Nematoda	0	0	10	640	640	320	0	0	0	0	0	0	0	560	0	0	0	80	0	240	0
Tricladida	520	0	10	1280	320	640	0	0	160	0	0	0	0	0	20	0	100	0	0	0	0
Nematomorpha	0	0	0	640	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hirudinea																					
Hydra	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ostracoda																					
Amphipoda																					
Isopoda																					
Decapoda																					
Mollusca																					
Collembola																					
Anthomyidae																					
Rotatoria																					

PR7 (no.m-2)

Date	2/88		12/87		10/87			6/87			4/87			2/87		
Replicate	B2	B3	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3
Plecoptera	0	0	80	0	0	0	0	10	0	0	20	0	10	0	0	0
Ephemeroptera	1480	40	1540	1260	180	10	10	10	30	0	2920	710	70	620	160	230
Simulidae	6400	270	12220	2590	40	210	50	130	10	10	2430	990	100	140	0	70
Chironomidae	6120	1640	4340	1770	5100	5540	6690	190	150	260	6810	1450	200	7420	7200	1600
Rhagionidae	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0
Ceratopogonidae	0	0	0	0	80	0	0	0	0	0	0	0	0	0	0	0
Empididae	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0
Tabanidae																
Tipulidae	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0
Chaoboridae	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Blephariceridae																
Culicidae	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0
Megaloptera	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0
Trichoptera	1080	30	2140	70	0	0	0	100	10	30	4770	830	50	600	80	160
Lepidoptera																
Coleoptera (ad)	0	0	0	0	0	0	0	0	0	0	80	0	0	0	0	30
Helodidae																
Elmidae-A	0	0	20	0	0	0	10	10	30	0	50	10	10	20	0	0
Elmidae-B																
Elmidae-C	0	0	160	0	0	0	0	0	0	0	0	0	0	20	0	50
Corixidae																
Gerridae																
Hydraenidae																
Hydrophilidae	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0
Hydroptilidae																
Dyticidae	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Belastomatidae																
Hemiptera	0	0	0	0	0	0	0	0	0	0	10	10	0	0	0	0
Notonectidae																
Naucorridae																
Hebridae																
Aeshnidae	80	0	0	0	0	0	0	10	0	0	30	10	0	20	80	0
Gomphidae																
Zygoptera																
Hydracarina	1360	0	0	10	0	0	0	0	10	0	0	10	0	0	0	40
Oligochaeta	5240	0	0	0	0	0	0	0	60	0	100	0	10	1620	0	90
Nematoda																
Tricladida	1960	0	0	160	0	0	10	0	0	0	180	20	0	20	0	10
Nematomorpha																
Hirudinea																
Hydra	11120	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0
Ostracoda	15400	0	80	0	0	0	0	80	10	0	1840	320	100	740	10320	0
Amphipoda																
Isopoda																
Decapoda	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0
Mollusca	560	0	200	120	0	0	0	0	0	0	180	0	0	0	0	0
Collembola	0	0	0	0	0	0	0	0	0	0	10	40	0	80	0	0
Anthomyidae																
Rotatoria	3200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

PRB (no.m-2)

Date	4/88			2/88			12/87			10/87			8/87			4/87			2/87	
Replicate	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B3
Plecoptera	80	190	160	40	0	150	690	260	0	540	70	940	40	480	210	50	320	0	160	0
Ephemeroptera	560	350	380	1560	120	2780	930	2020	450	260	460	500	140	1130	610	430	1290	20	320	280
Simulidae	0	10	2850	500	0	20	120	1440	1220	240	0	250	0	10	270	290	140	20	80	80
Chironomidae	2160	6650	4400	3610	2840	2570	5510	4960	2150	4280	2820	4570	4410	9250	5420	2270	3690	420	1600	2920
Rhagionidae	0	10	50	0	0	0	20	0	0	0	0	0	0	0	20	0	10	0	0	0
Ceratopogonidae	80	0	0	0	0	0	10	0	0	80	70	1600	30	0	0	40	40	0	0	0
Empididae																				
Tabanidae																				
Tipulidae																				
Chaoboridae																				
Blephariceridae																				
Culicidae																				
Megaloptera	0	0	0	0	0	0	0	0	0	10	0	10	0	0	0	0	0	0	0	0
Trichoptera	560	280	250	20	0	140	60	1000	140	50	120	200	40	160	200	70	50	0	240	160
Lepidoptera	0	0	0	0	0	0	0	70	0	0	0	0	0	0	0	0	0	0	0	0
Coleoptera (ad)	0	20	110	450	0	30	530	690	30	160	10	360	390	20	800	10	160	0	0	0
Helodidae	0	10	30	220	0	20	30	90	20	230	0	600	50	0	190	70	20	0	240	0
Elmidae-A	0	0	90	110	0	80	1470	640	380	1050	120	470	30	30	220	10	190	10	0	160
Elmidae-B	0	0	90	20	0	100	20	150	0	0	0	0	0	30	0	0	0	0	160	0
Elmidae-C	320	280	1560	870	80	480	1780	1700	60	450	140	2020	330	340	810	210	410	20	640	280
Corixidae																				
Gerridae																				
Hydraenidae	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hydrophilidae																				
Hydroptilidae																				
Dyticidae																				
Belastomatidae	0	1710	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hemiptera	0	10	10	0	0	320	0	0	30	0	0	0	0	0	0	10	0	0	0	0
Notonectidae																				
Naucorridae	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hebridae	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0
Aeshnidae	0	90	20	20	80	60	0	0	0	0	0	0	0	0	0	0	210	0	0	80
Gomphidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zygoptera	0	0	0	20	0	10	0	10	0	0	0	0	0	30	0	0	30	0	0	0
Hydracarina	2400	8690	1340	1010	560	3510	1150	1410	600	280	170	1200	220	1040	840	1490	80	230	480	2080
Oligochaeta	1760	390	160	270	360	80	160	270	50	70	60	720	40	380	1110	550	240	0	160	0
Nematoda	240	2040	70	0	80	360	10	0	20	20	140	0	380	320	160	510	160	10	0	0
Tricladida	0	0	20	10	0	10	0	0	0	0	0	0	0	0	0	20	0	0	0	0
Nematomorpha																				
Hirudinea																				
Hydra	160	650	0	0	0	320	0	0	0	0	0	70	0	0	0	0	0	0	0	0
Ostracoda	0	0	0	160	80	0	0	40	0	0	0	0	0	0	40	10	0	0	320	0
Amphipoda	0	10	0	160	0	0	0	30	20	30	0	250	80	1060	90	20	280	0	0	0
Isopoda	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0
Decapoda	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mollusca																				
Collembola	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	40	0	0	0
Anthomyidae																				
Rotatoria	0	0	0	0	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

PR9 (no.m-2)

Date	4/88			12/87			10/87			6/87			4/87			2/87		
Replicate	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3
Plecoptera	0	0	0	0	0	0	0	0	0	560	0	0	0	0	0	0	0	0
Ephemeroptera	340	10	610	2900	1560	5400	2790	8570	4570	50	900	320	160	200	160	300	200	1960
Simulidae	1550	10	2110	40	20	1690	1120	0	2260	80	4200	390	1230	2800	2890	640	550	6480
Chironomidae	12450	2330	620	740	640	5550	1500	890	1820	1620	2940	220	10840	4480	160	3240	4460	3280
Rhagionidae																		
Ceratopogonidae	0	0	0	0	0	0	0	10	0	0	0	0	0	40	0	0	0	0
Empididae	0	0	0	0	0	0	10	0	10	10	0	0	0	0	0	0	0	0
Tabanidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	120
Tipulidae																		
Chaoboridae	670	0	50	20	0	10	0	0	0	40	0	40	60	480	10	0	0	0
Blephariceridae																		
Culicidae																		
Megaloptera																		
Trichoptera	10	0	330	120	460	670	50	80	20	40	930	20	450	1880	20	140	590	580
Lepidoptera																		
Coleoptera (ad)	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Helodidae																		
Elmidae-A	0	0	0	0	0	0	0	0	10	0	10	10	0	0	10	0	0	0
Elmidae-B																		
Elmidae-C	0	80	0	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Corixidae																		
Gerridae																		
Hydraenidae																		
Hydrophilidae																		
Hydroptilidae																		
Dyticidae																		
Belastomatidae																		
Hemiptera																		
Notonectidae																		
Naucorridae																		
Hebridae																		
Aeshnidae	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0
Gomphidae																		
Zygoptera																		
Hydracarina	0	0	0	0	30	0	0	0	480	40	0	0	0	0	10	0	160	0
Oligochaeta	40	80	0	110	0	240	20	890	200	10	10	0	520	0	0	720	670	0
Nematoda	0	0	0	0	80	0	10	80	0	0	0	0	720	320	0	0	320	0
Tricladida	1030	50	0	230	780	0	160	1660	100	20	230	0	1020	1120	0	1620	320	20
Nematomorpha																		
Hirudinea																		
Hydra	0	0	0	0	0	0	330	720	40	170	0	0	0	0	0	0	0	0
Ostracoda	0	0	0	0	0	0	0	0	0	0	0	0	2080	800	10	0	0	640
Amphipoda	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40
Isopoda																		
Decapoda																		
Mollusca	0	0	10	0	10	210	0	0	0	0	0	0	0	0	0	0	0	0
Collembola	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0
Anthomyidae																		
Rotatoria																		

PR10 no.m-2

Date	4/88			12/87			10/87			6/87			2/87		
Replicate	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3
Plecoptera	0	0	0	10	0	0	320	0	0	320	70	20	0	0	0
Ephemeroptera	380	560	1270	810	660	880	2370	150	6140	1400	360	250	320	440	80
Simulidae	270	0	0	870	1680	50	0	0	100	60	10	190	0	440	320
Chironomidae	1250	230	3990	6500	15300	2760	2920	1980	1790	33410	5150	10200	21680	19440	8220
Rhagionidae	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceratopogonidae															
Empididae	0	0	0	150	0	0	0	0	0	50	10	0	400	0	20
Tabanidae															
Tipulidae															
Chaoboridae	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0
Blephariceridae															
Culicidae															
Megaloptera	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0
Trichoptera	590	0	0	1480	780	140	320	10	40	180	220	0	0	1200	330
Lepidoptera															
Coleoptera (ad)	0	0	0	0	140	10	0	0	0	0	0	0	0	40	0
Helodidae															
Elmidae-A	150	30	80	10	0	0	0	10	10	70	20	30	720	120	10
Elmidae-B															
Elmidae-C	30	0	0	0	80	0	0	0	0	350	0	0	800	360	0
Corixidae															
Gerridae															
Hydraenidae															
Hydrophilidae															
Hydroptilidae															
Dyticidae															
Belastomatidae															
Hemiptera															
Notonectidae															
Naucorridae															
Hebridae															
Aeshnidae	40	0	0	0	0	0	0	0	0	0	0	0	0	40	0
Gomphidae															
Zygoptera															
Hydracarina	320	0	320	160	0	80	0	0	0	320	320	160	0	0	10
Oligochaeta	0	30	0	0	1020	0	20	790	0	70	80	0	0	80	0
Nematoda	10	1120	0	50	20	0	0	80	0	10	0	0	0	40	0
Tricladida	20	70	0	0	10	20	0	170	30	0	10	0	320	40	0
Nematomorpha															
Hirudinea															
Hydra	0	0	0	0	0	0	4000	2200	30	0	0	0	0	0	0
Ostracoda	0	0	0	0	0	0	0	0	0	0	80	0	320	80	80
Amphipoda															
Isopoda															
Decapoda															
Mollusca	30	0	0	0	20	20	0	0	0	0	0	0	0	0	0
Collembola															
Anthomyidae	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0
Rotatoria															

EPHEMEROPTERANS

PR1	2/86			4/86			8/87			10/87			12/87			4/88		
	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3
Lestergella pencilliata	1	7	1	6	221	132	2	11	5	7	10	1		5				
Lithogloea harrisoni								5		1	2	23	1		1			
Aprionyx sp								9		5	9							
Castenophlebia calida		15	23	10	49	12	1	4		1	4	1	7	28	1			
Baetis harrisoni	1	11	10	87			8	3		1	10		4	11	14			
Baetis sp A			1															
Acentrella capensis (sp)			1															
Baetis sp B													2	6				
Baetis sp	1		5		136	16			2	1	3		1	6	4			
Acentrella B											10							
Leptophlebiidae adenophlebia																		

PR2	2/86			4/86			8/87			10/87			12/87			4/88		
	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3
Lestergella pencilliata				16			1		2									
Lithogloea harrisoni																		
Aprionyx sp					28													
Castenophlebia calida	1				18	8							1					
Baetis harrisoni	59	3		2	27		8		1				28	45	98			
Baetis sp A	30	2			16	8												
Acentrella capensis (sp)					9									1	3			
Baetis sp B													1	1				
Baetis sp	46	3	27						4				135	18	100			
Acentrella B														3				
Leptophlebiidae adenophlebia		24																

PR4	2/86			4/86			8/87			10/87			12/87			4/88		
	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3
Lestergella pencilliata																		
Lithogloea harrisoni																		
Aprionyx sp																		
Castenophlebia calida																		
Baetis harrisoni	24	2	1	18	6						4			8				
Baetis sp A			1			8												
Acentrella capensis (sp)																		
Baetis sp B					1													
Baetis sp					8	8												
Acentrella B																		
Leptophlebiidae adenophlebia																		

PR7	2/86			4/86			8/87			10/87			12/87			4/88		
	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3
Lestergella pencilliata				1	8													
Lithogloea harrisoni																		
Aprionyx sp			8															
Castenophlebia calida					1													
Baetis harrisoni	3	16								1	1		64		34			
Baetis sp A	17	1	8							8		1						
Acentrella capensis (sp)	8	1																
Baetis sp B										2								
Baetis sp	55	1	3							8			34		11			
Acentrella B															1			
Leptophlebiidae adenophlebia																		

PR8	2/86			4/86			8/87			10/87			12/87			4/88		
	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3
Lestergella pencilliata	4				24		4		72					1				
Lithogloea harrisoni							8			7								
Aprionyx sp	16																	
Castenophlebia calida	5	34	18	1	17		1		60	7	29	6	4					
Baetis harrisoni	19				8		7		44	3		12	8	112	22			
Baetis sp A	8																	
Acentrella capensis																		
Baetis sp B					9	1					13	13	1	1	1			
Baetis sp	3					9		32					8	582	6			
Acentrella B																		
Leptophlediidae adenophlebia																		

PR9	2/86			4/86			8/87			10/87			12/87			4/88		
	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3
Lestergella pencilliata																		
Lithogloea harrisoni																		
Aprionyx sp																		
Castenophlebia calida	6																	
Baetis harrisoni		2	1							66	47	184	58	39	330			
Baetis sp A	62	25	9															
Acentrella capensis	9	8	32									2	2		26			
Baetis sp B																		
Baetis sp	2		2									11	1	17	142			
Acentrella B												34		10	16			
Leptophlediidae adenophlebia																		

PR10	2/86			4/86			8/87			10/87			12/87			4/88		
	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3	b1	b2	b3
Lestergella pencilliata																		
Lithogloea harrisoni																		
Aprionyx sp			1												32			
Castenophlebia calida			4	8	8													
Baetis harrisoni	1			2	1	1				54		32	6	30	27			
Baetis sp A	6	13	2											2	32			
Acentrella capensis		8																
Baetis sp B										1								
Baetis sp	9	25	2			8				6		32	8	36	13			
Acentrella B										11		40	4	4	2			
Leptophlediidae adenophlebia			1		2													

TRICHOPTERANS

		4/88 PR1	2/88 PR1	12/87 PR1	10/87 PR1	6/87 PR1	4/87 PR1	2/87 PR1	4/88 PR2	2/88 PR2	12/87 PR2	8/87 PR2	6/87 PR2	4/87 PR2	2/87 PR2
HYDROPSYCHIDAE	Cheumatopsyche sp		3.33				6.67		10	3.33				3.33	30
	Macrostemum capense														
	other													6.67	
POLYCENTROPODIDAE						13.33									
ECNOMIDAE	Parencomina sp	3.33		6.67	10				20	260				3.33	1003.3
	Ecnomus sp														
	Ecnomus thomasseti														
HYDROPTILIDAE	Hydroptila capensis														
	Orthotrichia barnardi					3.33	3.33								
	Oxythira volocipes														
LEPTOCERIDAE	Trichosetodes sp					3.33		5	6.67	13.33	3.33				
	Athripsodes sp														
	Leptico helicotherce														
	other												3.33		3.33
PHILOPOTAMIDAE	Dolophilodes sp		3.33			3.33									
PETROTHRINCIDAE	Petrothrincus circularis		3.33	40	56.67	150		5							
PSYCHOMYIDAE						20						3.33			
GLOSSOMATIDAE	Agapetus sp														
STENOPSYCHIDAE	Stenopsyche ulmeriana														
OTHER			3.33			3.33				3.33					

		4/88 PR4	2/88 PR4	12/87 PR4	10/87 PR4	6/87 PR4	4/87 PR4	2/87 PR4	4/88 PR7	2/88 PR7	12/87 PR7	6/87 PR7	4/87 PR7	2/87 PR7
HYDROPSYCHIDAE	Cheumatopsyche sp	376.67			176.67	860	1056.6	533.33	26.67	435	1155	46.67	1526.6	150
	Macrostemum capense									20	30		10	
	other						290	26.67		20	160		200	53.33
POLYCENTROPODIDAE														
ECNOMIDAE	Parencomina sp													
	Ecnomus sp													
	Ecnomus thomasseti												3.33	
HYDROPTILIDAE	Hydroptila capensis									65			10	20
	Orthotrichia barnardi												3.33	3.33
	Oxythira volocipes													
LEPTOCERIDAE	Trichosetodes sp	10	536.67	53.3		66.67	53.33	40		5				
	Athripsodes sp													
	Leptico helicotherce													
	other					16.67	220							
PHILOPOTAMIDAE	Dolophilodes sp													
PETROTHRINCIDAE	Petrothrincus circularis													
PSYCHOMYIDAE														
GLOSSOMATIDAE	Agapetus sp												3.33	
STENOPSYCHIDAE	Stenopsyche ulmeriana													
OTHER								13.33						3.33

		4/88 PR8	2/88 PR8	12/87 PR8	10/87 PR8	8/87 PR8	4/87 PR8	2/87 PR8	4/88 PR9	2/88 PR9	12/87 PR9	10/87 PR9	6/87 PR9	4/87 PR9	2/87 PR9
HYDROPSYCHIDAE	Cheumatopsyche sp			216.67	40				70	70	310	16.67	156.67	213.33	126.67
	Macrostemum capense			23.33											
	other										3.33	3.33	160	136.67	
POLYCENTROPODIDAE				13.33											
ECNOMIDAE	Parencomina sp	250	36.67	26.67	40	56.67	10	20							
	Ecnomus sp	16.67						40	43.33	373.33					
	Ecnomus thomasseti														
HYDROPTILIDAE	Hydroptila capensis		6.67	6.67						26.67					50
	Orthotrichia barnardi		6.67	6.67				20		106.67		26.67		3.33	160
	Oxythira volocipes			3.33			3.33							3.33	
LEPTOCERIDAE	Trichosetodes sp			3.33	6.67										
	Athripsodes sp		20	50			13.33								
	Leptico helicotherce	3.33		3.33											
	other														
PHILOPOTAMIDAE	Dolophilodes sp			3.33	33.33	40									
PETROTHRINCIDAE	Petrothrincus circularis			30	10										
PSYCHOMYIDAE				3.33											
GLOSSOMATIDAE	Agapetus sp			13.33		26.67	3.33								
STENOPSYCHIDAE	Stenopsyche ulmeriana					3.33									
OTHER															

		4/88 PR10	2/88 PR10	12/87 PR10	10/87 PR10	6/87 PR10	2/87 PR10
HYDROPSYCHIDAE	Cheumatopsyche sp	86.67	43.33	116.67	16.67	66.67	180
	Macrostemum capense	3.33					
	other			566.67		3.33	240
POLYCENTROPODIDAE							
ECNOMIDAE	Parencomina sp						
	Ecnomus sp	3.33					
	Ecnomus thomasseti		6.67				
HYDROPTILIDAE	Hydroptila capensis		63.33	33.33		3.33	126.67
	Orthotrichia barnardi		53.33	53.33	3.33		40
	Oxythira volocipes						
LEPTOCERIDAE	Trichosetodes sp					6.67	
	Athripsodes sp						
	Leptico helicotherce						
	other					3.33	
PHILOPOTAMIDAE	Dolophilodes sp						
PETROTHRINCIDAE	Petrothrincus circularis						
PSYCHOMYIDAE							
GLOSSOMATIDAE	Agapetus sp						
STENOPSYCHIDAE	Stenopsyche ulmeriana						
OTHER							

e) Lake data (refers to Paper V)

JANUARY 1988 - LAKE DATA

SITE	DEPTH	TEMP	PH	DO	COND	TDS	TSS	CL	ALK	CYCLOPOID	CALANOIDS	NAUPLII	CDAPH	CHYD	BOSMINA	CHAOBORS
NR	T	25.3	4.53	92.21	33.5	39.25	2.8235	10.51		2250		2375	5375			
NR	T	25.8	4.18	94.74	34.5	36.25	3.1765	7.84		906.25		3125	8843.75	31.25	93.75	
NR	T	25.5	4.66	98.05	34.1	37.50	3.2941	7.84		5963.78		12718.75	48187.5	156.25		
NR	M	24.0	4.57	91.14	34.5	43.00	2.4600	7.84		3812.5		1562.5	4437.5			
NR	M	25.0	4.22	91.61	34.0	39.25	2.2353	9.51		5718.75	625	3593.75	11343.75			62.5
NR	M	24.0	4.91	96.21	36.1	40.00	1.7647	10.85		11968.75	31.25	6906.25	13625			
NR	B	21.2	4.86	90.36	34.7	39.75	2.8235	10.85		9062.5		3812.5	17031.25			
NR	B	24.0	4.67	91.82	34.4	31.75	2.2353	8.68		9562.5		6500	11656.25			
NR	B	21.0	4.85	96.43	38.8	41.75	2.9412	7.17		2656.25		1937.5	2656.25			
ND	T	23.8	4.95	92.41	42.2	22.50	3.4118	11.18		9406.25		11312.5	15406.25			281.25
ND	T	24.0	4.86	94.30	34.9	31.50	3.0588	12.01		6593.75		2037.5	11062.5			
ND	T	24.0	4.95	90.51	34.8	31.25	2.4706	10.85		6437.5		14625	14718.75			
ND	M	20.0	4.85	84.21	39.6	25.25	2.7059	7.18		1218.75		968.75	1781.25	31.25		31.25
ND	M	19.5	4.80	66.28	39.4	36.00	0.0001	11.35		2625.03		1718.75	1187.5			31.25
ND	M	20.0	4.80	77.19	43.4	39.75	2.3529	13.85		2456.25		2968.75	4718.75	62.5		31.25
ND	B	18.5	4.66	51.70	38.3	36.50	2.4000	10.51		1062.5		437.5	281.25			31.25
ND	B	18.5	4.70	47.73	37.7	37.00	2.8000	11.35		1625		1812.5	1093.75	468.75		
ND	B	18.5	4.65	44.89	37.1	38.25	2.6667	11.68		1465.75		1500	1218.75	156.25		62.5
AR	T	29.0	7.10	96.73	90.3	85.25	1.2941	21.69	0.1280	968.75	4718.75	31781.25	14625		750	
AR	T	27.1	7.60	92.31	91.8	79.75	2.3529	22.02	0.1477	1656.25	3593.75	11406.25	3562.5		968.75	
AR	T	26.2	7.12	88.61	91.7	79.75	0.8235	21.19	0.1427	1187.5	5000	24468.25		31.25	2406.25	187.5
AR	M	21.0	6.60	78.16	90.4	76.75	4.3529	20.52	0.1427	8562.5	29718.75	5343.75	16937.5		13937.5	218.75
AR	M	21.0	6.70	55.17	91.5	82.00	2.0000	21.69	0.1427	3187.5	7780.5	21250	6875		4031.25	31.25
AR	M	19.0	6.50	58.24	90.3	77.75	1.4118	22.02	0.1427	312.5	750	3906.25	156.25		31.25	
AR	B	18.0	6.60	34.41	89.5	71.25	4.0000	20.86	0.1674	1093.75	4625	9937.5	1375		1468.75	62.5
AR	B	18.0	6.70	25.27	87.3	35.25	1.0588	21.19	0.1575	500	843.75	6218.75	562.5	62.5	250	62.5
AR	B	14.5	6.00	12.56	95.6	71.50	2.3529	22.53	0.1333	125	812.5	4843.75			62.5	
AD	T	24.0	7.50	87.80	91.3	64.75	3.5294	21.25	0.1378							
AD	T	24.0	7.35	87.20	90.6	69.50	2.0000	21.25	0.1526	1656.25	6218.75	25625	9250		2937.5	468.75
AD	T	24.5	7.50	86.50	90.7	69.00	1.1765	21.92	0.1427	1375	6625	17000	5000		687.5	656.25
AD	M	18.2	6.45	9.24	96.0	89.75	4.3529	23.61	0.1329	812.5	1843.75	3937.5	812.5		93.75	93.75
AD	M	16.0	6.13	9.84	91.6	84.25	2.5882	21.92	0.1329	562.5	312.5	2062.5	343.75		93.75	437.5
AD	M	16.0	5.70	5.44	88.3	81.97	2.3529	19.56	0.1329	437.5	968.75	3375	312.5	31.25	93.75	250
AD	B	15.0	6.00	4.80	90.3	83.00	0.9411	21.25	0.1083	468.75	1000	2500	1093.75		125	125
AD	B	14.0	6.00	3.25	128.5	109.75	3.4118	30.35	0.1181	93.75	250	1343.75	218.75		93.75	
AD	B	14.0	5.90	5.75	87.1	50.00	1.5294	20.24	0.1181		281.25	1031.25	187.5		62.5	

JUNE 1988 - LAKE DATA

SITE	DEPTH	TEMP	pH	DO	COND	TDS	TSS	CYCLOPOID	CALANOIDS	NAUPLII	CDAPH	CHYD	BOSMINA
NR	T	11.3	4.41	98.49	43.10	44.50	1.6000	437.5			6500		
NR	T	11.0	4.21	97.60	37.10		2.6667	12718.75		1625	8437.5	31.25	
NR	T	10.8	4.30	100.00	43.40	31.25	2.2667	13000		2000	3281.25		
NR	M	11.3	4.39	97.60	48.90		1.2000	9687.5		718.75	4875	62.5	
NR	M	11.0	4.29	99.38	45.00	43.75	3.3333	11000		1562.5	5781.25		
NR	M	10.8	4.29	99.38	44.20	23.00	2.4000	11125		1062.5	4875		
NR	B	11.5	4.42	97.60	43.00		1.8667	8656.25		718.75	3500	156.25	
NR	B	10.8	4.43	99.38	44.20	46.75	3.4667	12218.75		2000	6812.5		
NR	B	10.9	4.43	97.60	37.60	39.25	2.8000	5312.5		625	4468.75		
ND	T	11.2	4.47	96.36	53.70		1.8667	1125		1562.5	3187.5	62.5	
ND	T	11.0	4.38	98.66	53.60	39.75	2.1333	843.75		1312.5	2531.25		
ND	T	11.0	4.38	99.09	53.20	22.50	2.0000	3312.5	125	3218.75	5562.5	187.5	
ND	M	9.9	4.44	94.74	54.70	44.25	1.4667	468.75	93.75	281.25	750	187.5	
ND	M	10.2	4.44	94.37	54.10	34.50	1.6000	718.75		875	1250	93.75	
ND	M	9.9	4.38	96.49	53.20	43.25	1.7333	281.25		31.25	593.75	62.5	
ND	B	9.7	4.39	92.64	52.90	34.00	1.7333	593.75		187.5	406.25	187.5	
ND	B	9.5	4.50	93.51	51.70	39.25	1.0667	562.5		187.5	531.25	125	
ND	B	9.5	4.36	93.94	52.50	43.25	1.6000	62.5		218.75	187.5	187.5	
AR	T	13.2	6.67	100.47		69.50	4.8333	218.75	1187.5	1281.25	31.25	500	93.75
AR	T	12.7	6.76	100.93		73.75	5.3333	62.5	562.5	1250	31.25	125	93.75
AR	T	12.1	5.87	100.00		62.00	5.6667	125	875	1281.25		62.5	1218.75
AR	M	12.0	6.78	100.00		75.00	7.5000	312.5	1343.75	1468.75			500
AR	M	12.0	6.86	100.00		59.50	5.1667						
AR	M	11.7	6.71	99.55		66.50	6.6667	93.75	1906.25	1906.25	62.5		1062.5
AR	B	11.7	5.66	98.18		82.50	5.1667	62.5	1093.75	1343.75	31.25		718.75
AR	B	11.7	6.91	97.76		58.00	16.6667	343.75	2531.25	4500			1468.75
AR	B	11.6	5.60	96.86		69.50	4.3333	1875	93.75	281.25	31.25	375	125
AD	T	11.7	6.00	98.17	98.00	54.00	7.0000	218.75	1031.25	1593.75	31.25	31.25	406.25
AD	T	11.7	5.90	99.54	97.80	59.50	6.1667	62.5	1187.5	2250	62.5		281.25
AD	T	11.7	5.94	100.00	95.60	73.25	5.0000	31.25	968.75	1906.25	125		250
AD	M	11.7	5.85	97.25	97.90	61.50	6.5000	93.75	1656.25	2312.5	187.5		312.5
AD	M	11.6	5.91	96.82	98.40	49.50	3.2000	62.5	1343.75	2343.75	156.25		250
AD	M	11.6	5.85	96.82	97.40	78.75	6.4000	93.75	2000	1250	93.75		156.25
AD	B	11.7	5.76	95.41	96.40	45.00	7.0000	93.75	968.75	937.5			156.25
AD	B	11.6	5.76	78.18	97.80	56.50	36.0000	656.25	812.5	1281.25	156.25	31.25	156.25
AD	B	11.5	5.80	91.82	92.60	56.00	6.0000	375	437.5	1375			187.5